FILAMENT WINDING: *its development, manufacture, applications, and design*

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Preface

The accelerated pace at which technology is advancing in this atomic and space age has created many demands for new basic materials and techniques. New products and new problems are constantly arising in this new technical environment.

Filament winding is a method of producing many components for the aerospace, hydrospace, and commercial industries. It has grown rapidly as a technique in the past five years. This technique of combining filaments (reinforcements) with resins (matrices) has led to products with exceedingly desirable strength-weight ratios. Though the strength-weight ratio has been a prime requisite, with little attention paid to the cost of increasing the ratio, it is foreseen that the method has a brilliant future in products for which cost is a competitive factor.

The techniques for producing many items require the application of advanced engineering design parameters. Combining the highest-strength reinforcements with properly balanced matrices leads to structural elements and parts of unlimited potential. New engineering materials are being developed rapidly, specifically for filament winding.

Many products are made by this process. They range from high-pressure cylinders, rocket motors, and space vehicles to fishing rods and gun barrels. Recently, the production of a filament-wound railway tank car was achieved. This tank car has a capacity of 22,500 gallons or 100 tons. It is over 9 feet in diameter and 55 feet long and weighs only 52,000 pounds, 18,000 pounds less than its competitive

steel tank car. It not only offers a higher payload-to-weight ratio than steel at a competitive cost but also has maximum corrosion resistance.

In this book, design criteria, reinforcement and matrix materials, manufacturing techniques, properties, test methods, suppliers, and various applications of filament winding are discussed. We believe that the book will serve as a source of information to research and development groups, to designers, to manufacturers, to consumers, and to marketing and sales personnel. We hope that it will stimulate further research on materials, development of techniques and equipment, and utilization of this new science for production of old or new items. The use of this technique is limited only by the ingenuity and imagination of the researchers and engineers who must solve the problems of the atomic and space age.

D. V. Rosato
C. S. Grove, Jr.

January, 1964

Acknowledgments

We gratefully acknowledge our indebtedness in the preparation of this book to the researchers whose vision and productivity led to the development of filament winding; to the designers and engineers who utilized the techniques in new structural concepts and production items; to the authors and publishers whose articles have furnished much of the data and information; to the manufacturers who have cooperated in furnishing illustrations and data; to the several technical societies (SPI, SPE, AIAI, and SAMPE) that have permitted use of manuscripts; and to our wives, Virginia Rosato and Suzanne Treadwell Grove, whose encouragement, patience, and forebearance made preparation of this book possible.

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Contents

1 **INTRODUCTION, 1**

History, 4
Textiles, 7
Advantages, 9
Limitations, 11
Products, 14
Statistical Estimates, 14
Research Problems, 16
References, 18

2 **APPLICATIONS, 19**

Storage Tanks, 20
Pipe, 22
Aerospace, 26
Missiles, 27
Hydrospace Vehicles, 33
Guns, 36
Electrical Equipment, 41
Aircraft, 42
Production Forecast, 43
References, 44

3 **REINFORCEMENTS, 46**

Glasses, 46
Metals, 66

Tapes, 82
References, 86

4 RESINOUS MATRICES, 88

Epoxy Resins, 90
Polyester Resins, 93
Phenolic Resins, 95
Silicone Resins, 98
Polybenzimidazole Resins, 99
Other Resinous Matrices, 99
Other Matrices, 100
Surface Treatment of Reinforcement for Bonding, 101
Impregnation of Reinforcement by Matrix, 103
Summary, 109
References, 110

5 MANUFACTURING, 113

Types of Machines, 113
Methods of Winding, 119
Mandrel, 127
Tensioning Filaments or Tapes, 135
End Closures, 140
Liners, 140
Integral Case Winding, 141
Foldable Containers, 142
References, 144

6 FACTORS AFFECTING PROPERTIES, 145

Fabrication Variables, 146
Processing Variables, 147
Winding Variables, 148
Size Variables, 148
Material Variables, 149
Environmental Factors, 153
Stress Variables, 163
General Summary, 165
References, 168

7 DESIGN CRITERIA, 171

Geometrics, 171
Stresses, 180
Designs, 189
Basic Relationships Governing Ideal Structures, 216
Large Case Design, 229
Segmented Case Concept, 231
Data, 234
External Pressure Vessels, 245
References, 247

8 TEST METHODS, 249

Specifications, 249
NOL Ring Test, 250
Compressive Tests, 256
Hydrostatic Burst Test, 259
Cyclic Fatigue: Pressure Tests, 260
Critical Collapse Test of Thin-Wall Cylinders, 269
Soak-Cycle Test, 277
Resin Tests, 280
Nondestructive Testing, 287
Experimental Testing, 291
Basic Tests, 292
Quality Control, 311
References, 326

APPENDIX A, Companies with Filament Winding Facilities or Capabilities, 329

APPENDIX B, Suppliers of Reinforcements, 332

APPENDIX C, Suppliers of Resins, 334

APPENDIX D, Suppliers of Preimpregnated Reinforcements, 336

APPENDIX E, Glossary, 337

INDEX, 351

1 Introduction

The use of circumferential wrappings to increase the bursting strength of certain structures is not new. Historically, wire wrappings have been used to prevent bursting of cannon barrels and to wrap wooden pipes both to increase the bursting strength and to hold the two parts together so that a leak-proof cylinder is formed. However, the use of filamentary structures for applications requiring ultimate structural performance is recent and unique. Filament winding is a fabrication technique for forming reinforced plastic parts of high strength and light weight. It is made possible by exploiting the remarkable strength properties of their continuous fibers or filaments encased in a matrix of a resinous material, either organic or inorganic.

For this process, the reinforcement consists of filamentous nonmetallic or metallic materials processed either in fibrous or tape forms. Most frequently used at the present time is some form of glass: continuous filament, roving, yarn, or tape. The glass filaments, in whatever form, are encased in a resin matrix, either wetted out immediately before winding (wet process) or impregnated ahead of time (preimpregnated process). The resin fundamentally contains the reinforcement, holding it in place, sealing it from mechanical damage, and protecting it from environmental deterioration. The reinforcement-matrix combination is wound continuously on a form or mandrel whose shape corresponds to the inner structure of the part being fabricated. After curing of the matrix, the form may be discarded or it may be used as an integral part of the structural item (1).

Filament winding is carried out on specially designed automatic machines. Precise control of the winding pattern and direction of the filaments are required for maximum strength, which can be achieved only with controlled machine operation. The equipment in use permits the fabrication of parts in accordance with properly designed parameters so that the reinforced filamentous wetting system is in complete balance and optimal strength is obtained. The maximum strength is achieved when all major stresses are carried by filaments in tension. Under proper design and controlled fabrication, hoop tensile strengths of filament wound items can be achieved of over 500,000 psi, although a strength of 210,000 psi is more frequently achieved.

Since this fabrication technique allows production of strong, light weight parts, it has proved particularly useful for components of aerospace, hydrospace, and military applications (Table 1.1) and for structures of commercial and industrial usefulness (Table 1.2). Both

Table 1.1 Filament-Wound Structures for Aerospace, Hydrospace, and Military Applications

Rocket motor cases	Liquid rocket thrust chamber
Rocket motor insulators	Rocket exit cones
Solid propellent motor liners	Chemical rockets
Nose cones for space fairings	Chemical tanks
Rocket nose cones (2)	Sounding rocket tubes
Rocket nozzle liners	Tactical bombardment rockets
Jato motor	Tent poles
APU turbine cases	Heat shields
High-pressure bottles (gas or liquid)	Artillery shell shipping grommet
Vacuum cylinders	Artillery round-protective cones
Torpedo launching tubes	Submarine fluid pipes
Rocket launcher tubes	Submarine tanks and containers
Flame thrower tubes	Submarine ventilation pipes
Missile landing spikes	Submarine hulls
Deep space satellite structures	Underwater buoys
Radomes	Cryogenic vessels
Igniter baskets	Electronic packages
Wing dip tanks	Submarine fairwaters
Helicopter rotor blades	Sonar domes
Thermistors	Engine cowlings
Missile shipping cylinders	Fuse cases
Boat ventilator cowlings	Torpedo cases and launchers

Tabl 1.2 Filament-Wound Structures f r Commercial and Industrial Applicati ns

Railway tank cars (3)
Storage tanks: acids, alkali s, water, oil, salts, etc.
High-voltage switch gears
Electrical containers
Propellers
High-pressure bottles (4)
Decorative building supports
Containers for engines, batteries, etc.
Buoys
Valves
Aircraft tanks
Aircraft under-carriage
Aircraft structures
Fishing rods (5)
Round nose boat
Boat masts
Lamp poles
Golf clubs (6)
Race track railing
Auto bodies (7)
Drive shafts
Air brake cylinder
Heating ducts
Acid filters
Recoil-less rifle barrel
Pontoons
Motor housing
Computer housings
Marker buoys
Laundry tubs
Ventilator housings
Rifle barrel (1)
Dairy cases (8)
Auto and truck springs
Circuit breaker rupture pots
Cartop boats
Electroplating jigs

Irrigation pipes
Salt water disposal pip s
Underground water pipe
Oil well tubes
Ladders
Extension arms for telephone trucks
Textile bobbins
Weather rockets
Gas bottle-mines
Structural tubing
Insulating tubes
Electrical conduit
Chemical pipe
Pulp and paper mill pipe
Water heating tanks
Pipe fittings and elbows
Truck-mounted booms
Highway stanchions
Capacitor jackets and spacers
Coil forms
Electronic waveguides
Printed circuit forms
Electric motor rotors, binding bands
Circuit breaker housing
High-voltage insulators
Rectifier spacers
Antenna/dishes
Rotating armatures—DC motors
DC commutator
Fan housing
High voltage fuse tubes
Floating ducts
Automotive parts
Tank trucks
Light poles
Brassiere supports
Looms

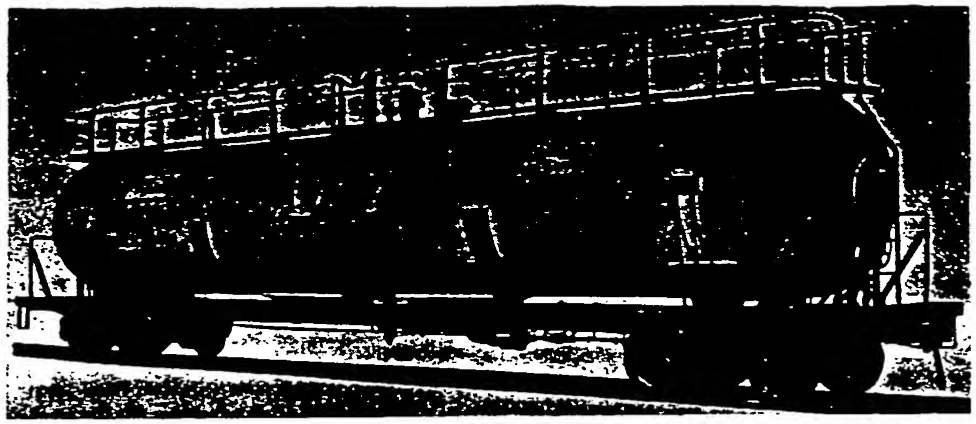


Figure 1.1 Glass epoxy filament-wound 9-foot-diameter by 55-foot-long assembled railway tank car. (Courtesy of Black, Sivalls and Bryson, Inc., and *Reinforced Plastics.*)

the reinforcement and the matrix can be tailor-made to satisfy almost any property demand. This aids in widening the applicability of filament winding to the production of almost any military or commercial item wherein the strength to weight ratio is important. Filament winding recently has been used to produce rectangular shapes (8).

HISTORY

The high strength of glass fibers has been of great interest for many years. In 1920, Griffith (9) reported strengths of freshly drawn undamaged fibers of up to 900,000 psi. Commercial glass fibers of the continuous filament type have been tested at 250,000 to 300,000 psi. However, the tensile strength of the glass filaments is highly dependent on the presence of mechanical flaws and on the environmental conditions (10). Minute cracks and adsorbed water vapor definitely lower the breaking stresses of filaments to a great degree.

In general, carefully selected glass marbles of the proper composition are melted in bushings containing a large number of orifices. The number of fibers drawn from a single bushing is collected on a winding tube, to form a single continuous strand. Surface speeds of the tube may reach 12,000 fpm. An important part of the drawing operation is the application of the sizing to the grouped filaments before winding. This sizing consists of agents used to lubricate the individual filaments, to minimize mechanical damage, and to bind the textile strands together. A common sizing is a starch-oil mixture (11), which furnishes both lubrication and binding.

In considering reinforcements, the tensile strength of the filaments is very important. Under this parameter, glass is outstanding, as evidenced by Table 1.3, which compares the tensile strengths of various fibrous materials. The strengths are reported in grams per denier, which is a commonly used textile term. Roughly, in glass filaments one gram per denier corresponds to about 31,000 psi. While glass filaments are more susceptible to mechanical damage than other fibers tested and are also weakened by a high humidity environment, they are in general stronger and resist higher temperatures of use than many other fibers.

Reinforced plastics are composite systems consisting of matrices of resin in which fibrous reinforcements are contained. Considerable choice is allowable in the types of resins and ratios of resins to reinforcement, which result in products with quite a range of properties. Some of the advantages are good physical properties of high strength-weight ratios, resistance to chemical attack, electrical resistivity, and suitability for fabrication by various methods (13).

The materials used in the construction of rocket boosters and aerospace vehicles range from special high-density substances for heat absorption to high-strength, lightweight substances to carry the structural stresses. For each application the requirement for minimum weight is a controlling factor. This minimum weight parameter is also highly important in many commercial structures, such as railway tank cars. Many available materials generally possess only one outstandingly good property. Thus, the ideal new material is a properly

Table 1.3 *Tensile Strengths of Fibrous Yarns (12)*

Yarn	Tensile Strength, grams per denier
Glass (filament)	6.3–6.9
Cotton	3.0–4.9
Wool	1.0–1.7
Viscose, regular	1.5–2.4
Acetate, regular	1.3–1.5
Nylon, regular	4.7–5.6
Orlon	4.4–5.2
Dacron	4.0–5.0
Vinyon	0.7–1.0
Jute	1.6–1.9

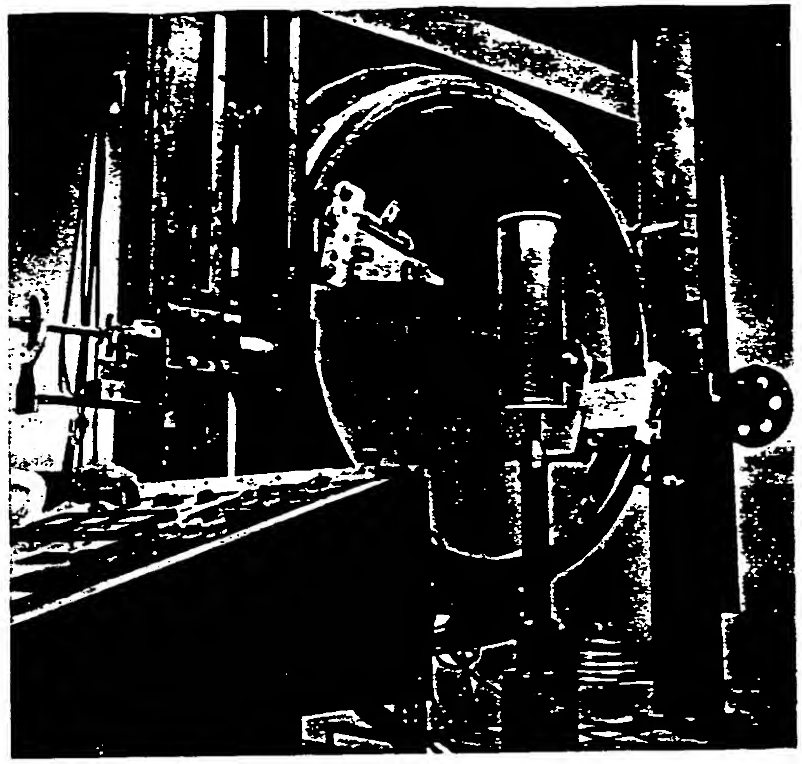


Figure 1.2 Fabrication of filament-wound electric battery case. (Courtesy of Narmco Research and Development.)

blended composite of two or more basic materials; each component contributes its own best property to the final composite.

Since 1947, various government agencies have been conducting and sponsoring intensive research and development efforts to apply the filament-wound structural concept to the production of strong lightweight pressure vessels. The basic work conducted on glass-reinforced plastic materials, originating about 1940, provided the background design data for the development of pressure vessels for rocketry (14). The end items of this research and development effort are the production units of filament-wound motors or cases for missiles such as the Atlas and Polaris.

A pressure vessel may be defined as a structure capable of containing fluid under pressure or of withstanding an external fluid pressure. Internally contained pressure vessels require high tensile strength loading characteristics for atmospheric or aerospace operations. The shape of an internally loaded pressure vessel is usually either spherical or cylindrical. With some loss of efficiency, it is possible to produce

almost any desired shape. On the other hand, externally loaded pressure vessels are subjected to compressive stresses to operate in hydrospace or under water. It is obvious that for this use, too, a sphere offers the best design characteristics, since of all geometric shapes it provides the maximum volume for a given surface area (15).

As discussed earlier, a glass-reinforced plastic material offers the greatest strength-weight efficiency, or specific strength. In designing with this composite system, the load-carrying reinforcement fibers are oriented in a unidirectional manner so that their optimum tensile strength is utilized within a given envelope of the geometry of the structural item. This filament-wound composite material is used to develop a balanced structure. In an application, such as a rocket motor body, where end closures and attachment areas are to be located on the filament-wound structure, an oblated spheroid provides the optimum geometric configuration.

TEXTILES

For many decades, the textile industry in the United States has grown and expanded to produce necessary yarns, woven and knitted fabrics, and other products for military, civilian, and industrial consumption. The techniques of spinning of the natural indigenous fibers of cotton and wool, have been extended to other fibers. Utilization of the spun fibers in the manufacture of cloth, tapes, and a multitude of other forms has permitted expansion of the textile industry into a very important segment of production. Historically, cotton was king; but many recent developments of synthetic fibers, including chemical modifications of natural fibers, have forced cotton into a less prominent position in the final consumer's market.

In spite of the importance of the textile industry, major new fibers, finishes, and treatments have not come from textile research, per se, but from the research and development laboratories of the American chemical industry. This newer textile industry has, however, borrowed heavily from the older textile industry in equipment design and operating techniques. The warping, roving, weaving, and knitting machinery of the new fibers are largely modified and improved versions of similar machinery long used in various manufacturing operations for the older and/or natural fibers.

The development of glass-filament yarn, roving, and warps has depended largely for equipment on the textile engineers and designers. Important tensioning devices are adaptations of similar items from the textile industry. Adjustable bars, spring-loaded clamps, camel

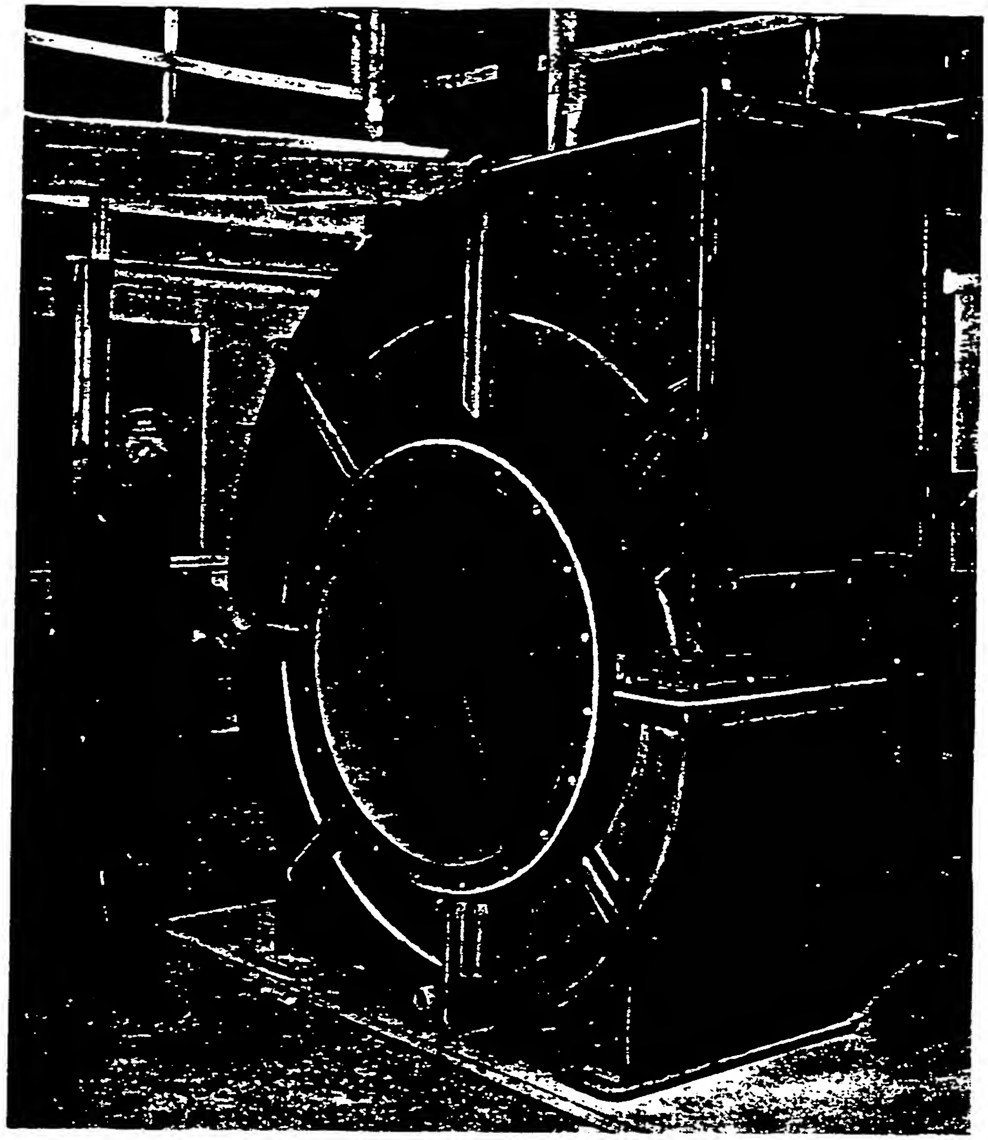


Figure 1.3 Typical production fan installed in a pulp mill incorporating glass fabric–polyester resin tape wound tubes. (Courtesy of Hoganas-Billesholms A B, Sweden.)

backs, and brakes on the wrapped warp for tension control during filament winding have long been used by knitters and weavers. The equipment to control the angle of winding with its traversing mechanism was originally developed for winding or roving on tubes or warps or for yarn on cones. Even some of the rotating mechanisms for filament winding owe their concepts to the textile industry. Thus the

new and unique filament-winding industry has made full use of the pertinent historical techniques developed by the textile industry.

The importance of scientific research as a necessary facet of industrial development of new product enterprises is recognized and accepted. The potential of scientific research in the natural resource enterprises is neither generally recognized nor appreciated. The textile industry comprises one of the oldest and largest areas of natural resource enterprise (16). While the textile industry has been reluctant to adopt modern research methods, the filament-winding industry has created new demands for the analysis, design, and use of textile materials. Thus the new, using the best of the old, is helping by research developments to improve the old.

The properties of filament-wound composite items are dependent on factors in addition to the basic properties of the reinforcement and matrix. Two of the most important factors, which contribute to highly efficient structures, are the design of the winding pattern and the processes of fabrication. Though these factors cannot provide capabilities greater than the inherent properties of the component materials, their optimization insures the most efficient utilization of the materials. Textile techniques play important roles in handling reinforcements so that optimum structural properties can be developed.

At present, much of the special equipment to produce filament-wound structures is designed and developed principally by the end-product fabricator based on proved textile techniques. It can be predicted, however, that in the near future this equipment will be designed and manufactured by companies that now supply the standard textile industry equipment.

ADVANTAGES

The ultra-lightweight requirements for solid rocket motor cases and for many other military and commercial uses have opened up a completely new field of problems concerning high-strength materials such as aluminum alloys, stainless steels, and other alloy steels. Recent studies have shown that the reliable use-strength level is limited by the inherent toughness or notch sensitivity of the materials. Toughness decreases in metals as strength is increased. Reduced weight (increased strength) and improved reliability (increased toughness) are opposing properties. Present alloy steels are notch-sensitive above approximately 200,000-psi tensile yield strengths. Problems caused by notch sensitivity may be reduced by utilizing ideal fabrication techniques. However, the small improvements achievable by better

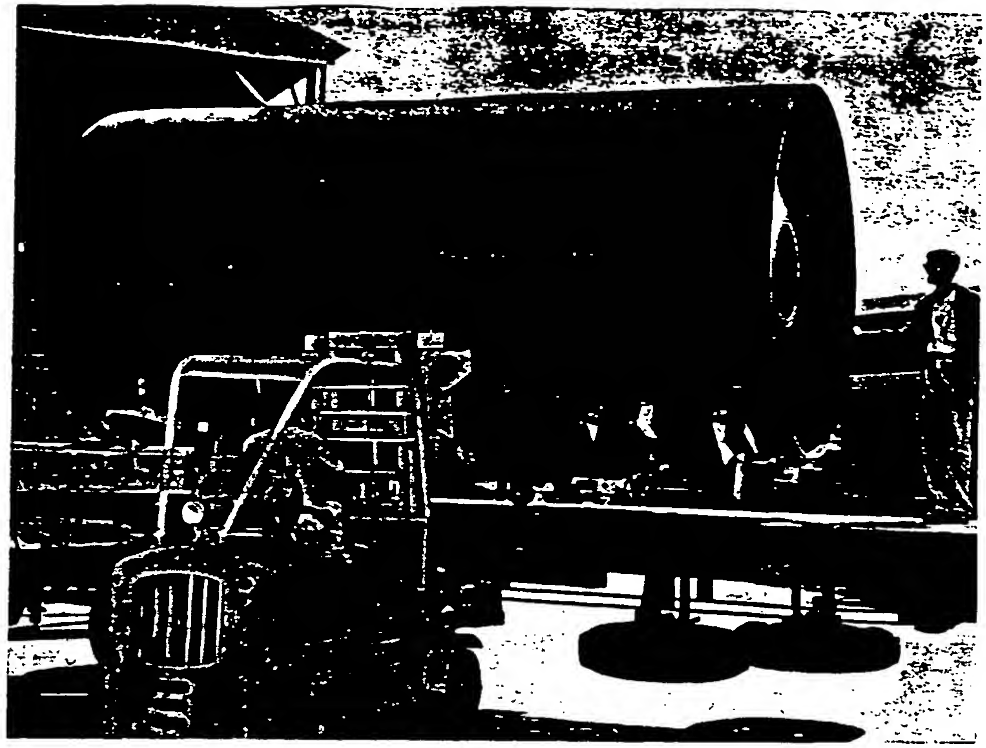


Figure 1.4 Structural glass filament-wound missile propellent tank; 8-foot diameter by 17 feet long, weighing 950 pounds. (Courtesy of Douglas Aircraft Co.)

fabrication do not satisfy the ultimate requirements for vessels of still lower weight. The filament-wound structure is extremely valuable in providing a solution to this basic problem. For example, in solid fuel rocket hardware, the filament-wound structures appear to be superior to all other current structural materials from a strength-weight point of view and to offer a number of advantages in fabrication, assembly, and cost.

Other disadvantages of metals for manufacture of various components of aerospace, hydrospace, and commercial equipment are their poor thermal insulation, poor heat capacity (absorptive or ablative), and high capital outlay for fabrication. As the state-of-the-art of filament winding improves, products made by this technique will become more profitably exploited (17). The startling advances of reinforced plastics in this new space and nuclear age permits their penetration into many areas in which metals were formerly primary materials of construction. It appears that the use of metals in aerospace vehicles will become rapidly reduced in amount and even obsolete.

Directional strength ratios can be varied in filament-wound structures. This enables one to design structures in which the material is utilized with a high level of efficiency (18). No more strength than that which is actually required needs to be provided in any one direction. This advantage is lacking in isotropic materials such as metal sheets. A typical example of unidirectional strength is given by internally loaded pressure cylinders, wherein the major stress is circumferential bursting. Filament winding provides high bursting strengths in such items.

The basic winding process is adaptable to a high degree of mechanization and automation, which results in production economy. There are no size limitations in either the reinforcement or matrix base materials which inhibit or complicate the design and construction of large structures. The equipment for fabrication of filament-wound items is often less cumbersome, intricate or costly than equipment for manufacturing similar items from metals.

In addition to withstanding internal pressures, filament-wound tanks for either military or commercial applications are generally required to carry handling and erection loads, axial and bending stresses. When thin-walled cylinders are theoretically analyzed, it is determined that for the lower stages of long-range missiles or space-exploration rockets, the load requirements are dictated by the axial compressive loads. The critical compressive load requirements can be met in filament-wound structures by utilizing a sandwich structure and/or adding longitudinal stringers. A honeycomb core used in a sandwich composite structure (19) as a stiffener offers a wider margin of safety than longitudinal and ring stiffeners. The honeycomb structure also provides substantial weight savings. Filament-wound structures with honeycomb cores are resistant to vibration, shock, sonic energy, and high-velocity impingement problems. In addition, such construction offers better dissipation or insulation to heat and radioactivity. A properly designed core sandwiched between two filament-wound skins gives excellent resistance against penetration of bullets and other projectiles.

LIMITATIONS

Filament-wound structures present certain problems because of the lack of ductility in the glass reinforcement. These can be partially solved by proper design and fabrication procedures. Reinforcements other than glass can be used to obtain good ductility, but many of these have lower-temperature characteristics. Proper construction

constitutes a well-proved means of utilizing an intrinsically nonductile reinforcement to obtain a high degree of confidence in the structural integrity of the end product. Since glass has high strength and is a low-cost product, glass filaments are still the major reinforcing material. Development, however, continues on newer filaments for applications requiring higher temperatures or greater stiffness. Other fibrous materials under study for use alone or in combinations include quartz, asbestos, ceramics, and metals (19).

A further difficulty with the basic materials is that they do not lend themselves readily to simple concepts and to simple comparisons (20). The matrix components are essentially the same resins as those used for conventional reinforced plastic laminates. Epoxy resins are more widely used than others, although phenolics and silicones give structures with higher temperature properties. Polyesters are used for many commercial structures in which cost is a problem and high temperatures do not prevail.

For certain filament-wound vessels the low modulus of elasticity of the glass-resin material is a serious disadvantage. Only moderate

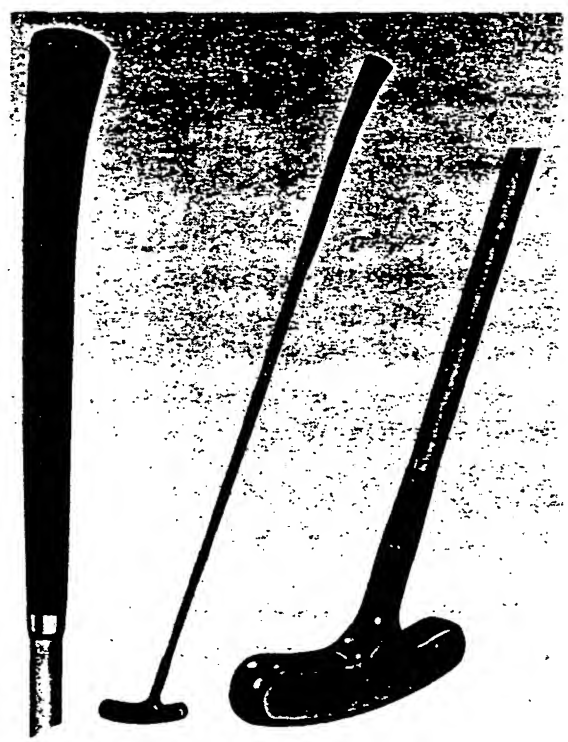


Figure 1.5 Glass fiber tabular golf club shaft. (Courtesy of Columbia Products/Shakespeare Co.)

improvements in modulus of elasticity by modifications in glass composition or in processing appear to be feasible. Any significant improvement in modulus will require changes in the glass composition. Such changes will pose new problems in manufacturing of the glass and in bonding it with the resin matrix. The most effective additive to the glass to increase its modulus without proportional increase in density is beryllium oxide. Filaments of this composition are now commercially available. They are expensive and relatively difficult to manufacture. Manufacturing experience is limited.

Interlaminar shear constitutes one of the possible limitations on filament-wound parts. Although the absence of interweaving boosts tensile strength by eliminating cross fraying, shear strength is limited by the bonding of the reinforcement to the resin. In conventional woven cloth laminates, the high points of one layer tend to interlock with the low points of adjacent layers. This results in strengthening of the composite against shear failure. Compared to other resins or matrices epoxy resin gives better interlaminar shear because of its inherently better bonding. By proper design, the low values of interlaminar shear can be minimized.

Filament-wound structures have lower ultimate bearing strengths than conventional laminates, for they are more rigid and less ductile. Accordingly, they have less ability to absorb stress concentrations around holes and "cut-outs" (21). The original higher tensile strength permits allowable design stresses under these conditions. Since cutting, drilling, or grooving for attachments or access openings reduces the high mechanical strength of filament-wound structures, proper design is necessary. Damaging machining operations are to be avoided after final curing of the part. Destructive "cut-outs" or attachment holes are to be eliminated by incorporating the use of premolded plastic or metal inserts into the designs.

Filament-winding techniques cannot be used for every structural element. The shape of the part must permit removal of the winding mandrel after final curing. Reversed curvatures should be eliminated whenever possible, since it is difficult to wind them and hold the filaments under tension. In order to meet this problem, fusible, expandible, and multipart mandrels are often required.

The cost of filament-wound parts is low only when volume production is achievable. Manufacturing processes should be mechanized and completely automated to obtain, by extensive and careful tooling, the close tolerances which are required in filament-wound structures to meet high-strength but low-cost objectives. Precision winders (22) with carefully selected mandrels and speed controls, special curing

ovens, and matched grinders are required. It takes time to develop this equipment, and a high initial investment is necessary. Once the original tooling cost has been amortized, the unit cost of individual filament-wound parts becomes relatively low, since the basic materials have a low cost.

PRODUCTS

The combination of basic materials used in producing filament-wound structures results in high strength-to-weight units. The composite structures also provide other properties which make them attractive for use in diversified application. Tables 1.1 and 1.2 list many of the military and commercial items fabricated by filament winding. These items are corrosion-resistant, nonmagnetic, watertight, low in cost, electrically nonconductive but transparent, and easy to maintain. Despite steadily increasing production, the vast potential of these procedures has not been fully exploited. One of the major applications is in military products, such as rockets and missiles.

The demonstrated feasible use of strong lightweight containers for handling and storage of corrosive liquids has stimulated investigation by designers into storage tanks of all types and sizes. At one-quarter the weight of mild steel, filament-wound tanks compete in many applications offering lower shipping costs, longer life, and reduced maintenance. Chemical storage tanks have been built with capacities of up to 400 barrels (42 gallons per barrel). These tanks are 12 feet in diameter, 20 feet in height, and weigh about 1500 pounds (23). Filament-wound railway tank cars represent another important product, in which the manufacturers take advantage of the design potential and economics. A 20,000-gallon tank car weighs 5,000 pounds less than a conventional steel car.

The dielectric property of filament-wound materials combined with the high strength provide the electrical engineer with a new approach to functional equipment design. Applications in this area include high-voltage switch gear (fuse tubes) and oil well pipe. The filament-wound oil pipe is used to contain magnetrons to utilize radio-frequency heating of the oil in relatively porous earth. The heated oil expands for facilitated pumping and production.

STATISTICAL ESTIMATES

It was estimated in 1952 that plastics production would be as follows: 1955—3.4 billion pounds; 1960—6.9 billion pounds; 1965—10.4 billion pounds; 1970—13.9 billion pounds; 1975—17.5 billion pounds.

While the actual figure for 1955 was 3.4 billion pounds and the actual figure for 1960 was 6.1 billion pounds, an estimate by experienced plastics engineers in 1963 predicts the total plastics production in 1967 to be 11.7 billion pounds, with a forecast of 13.9 billion pounds in 1970 (24). This prediction is based on an extrapolation of actual production figures released by the Department of Commerce in October, 1962. The amount of resins actually going into reinforced plastics in 1962 was 280 million pounds, or 3.61 per cent of the 7.8 billion pounds produced.

The resins of direct and most valuable import on the filament-wound structures program are the epoxy and phenolic families. These resins have higher temperature characteristics than some of the polyesters and for this reason are preferred. In 1962, 37 million pounds of epoxies were used in reinforced plastics and 12 million pounds in related adhesives and bonding (25). Estimates for 1967 are for 71 million pounds in reinforced plastics and 19 million pounds in adhesives and bonding. These figures compare to the use of phenolics for all lamination, including in 1962 87.3 million pounds of reinforced plastics, with an estimated use of 133.7 million pounds in 1967 (26).

In the summation of filament-wound uses of total resins, in 1962, 12 million pounds were used for pipes and tanks and 30.1 million pounds for aircraft and missiles (27). Comparable estimates for 1967 are 21.8 million pounds for pipes and tanks and 48.5 million pounds for aircraft and missiles. The forecasted estimates are based on extrapolation of present growth rates, which can be materially changed by major breakthroughs in resins, reinforcements, or fabrication techniques. The figures quoted cover all uses of resins and show a trend, although in these two areas about 50 per cent of the production and consumption at the present time is for filament-wound structures.

The statistics on reinforcements or fiber production are even more revealing as the filament-wound potential is considered. Table 1.4 shows the distribution of the total fiber market in 1961 and 1962,

Table 1.4 Percentage of Total Fiber Market

Fiber	1961	1962
Cotton	64	61
Wool	6	5.5
Cellulosics	17	18
Noncellulosics	11	13
Textile Glass	2	2.5

Table 1.5 1962 United States Production of Synthetic Fibers

Fiber	Millions of Pounds	Percentage Change since 1961
Acetate	351.7	+16
Rayon	920.4	+16
Noncellulosics	970.4	+29
Textile Glass	188.5	+26
Total	2431.0	+22 average

which indicates a high relative increase in the total use of textile glass, much of which goes into filament-wound items (28). The change in production of United States synthetic (man-made) fibers comparing 1962 production to 1961 is shown in Table 1.5. The increase in use of textile glass is 26 per cent; much of this can be attributed to the heavy expansion of the filament-wound industry and its preponderant use of glass filament materials.

RESEARCH PROBLEMS

Filament winding is a new and novel concept of structural fabrication, which seeks to utilize the best properties of reinforcement and matrix to achieve end products of optimum and maximum usefulness. Government-sponsored programs have fostered and will continue to foster its development. Commercial programs have entered into prominence to fully exploit the potential of this concept. However, there are still many problems which need continuing research and development for fullest realization and utilization of filament winding.

The filament-winding process in its broadest scope covers a number of interrelated problems, which together contribute to the highest-quality finished structure (29). These problem areas for research and development may be divided into a series of categories. First and perhaps primary are studies to develop higher-temperature and higher-strength materials, both reinforcements and matrices. In order of importance, selection of synergistic materials is necessary to achieve optimum utilization and maximum strength to weight ratios of structural elements, which will meet and satisfy other criteria of corrosion resistance, electrical resistivity and permeability, long life, low maintenance, and good weathering characteristics.

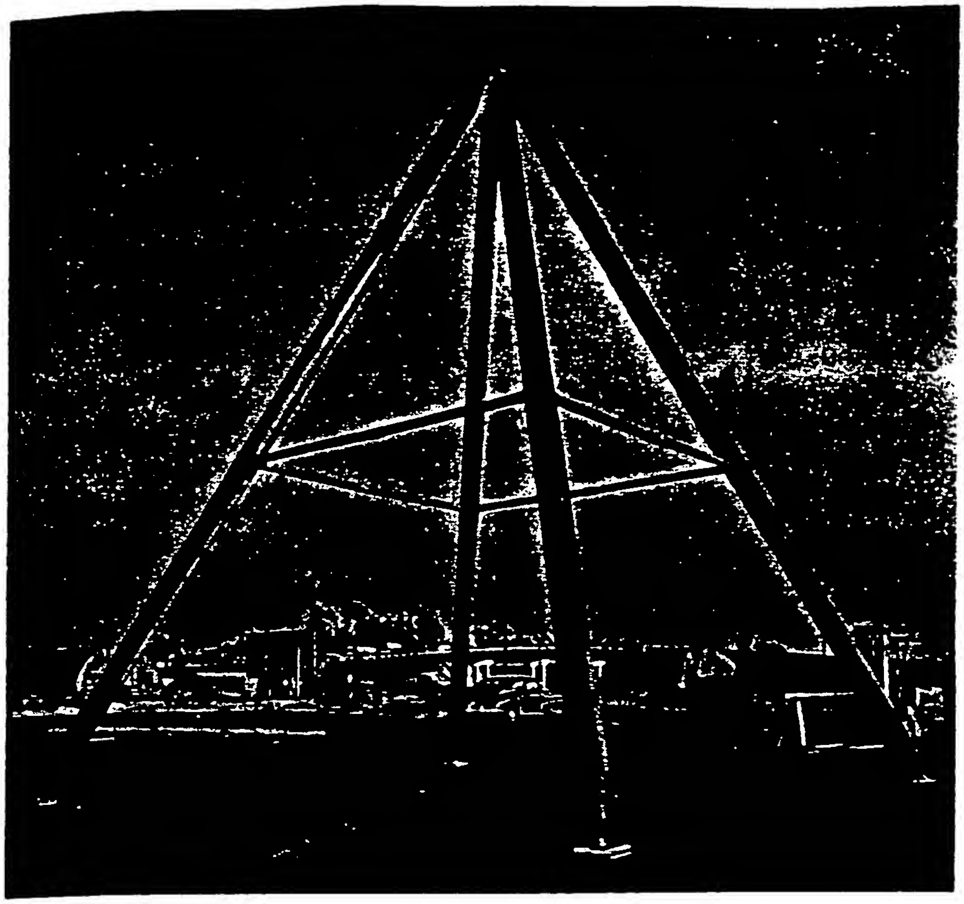


Figure 1.6 Tubular feet support for subreflector of large radiotelescope. (Courtesy of Advanced Structures, Division of Telecomputing Corp.)

Detailed design parameters need to be developed and optimized under well-considered principles of stress analysis. This will aid in achieving maximum strengths in structures based on the available reinforcements and matrices.

The fabrication process needs further development, making use of the experience and skill of the textile engineer and related competences. This processing development includes tooling, equipment, process variables, automation, controls, and finishing operations.

Finally, the finished structures must be fabricated under good quality control, since the final product is susceptible to changes in raw materials and processing. Test methods, both destructive and nondestructive, need full definition for the complete range of conditions from the received reinforcement and matrix materials through the finished product. The standardization and use of widely recog-

nized and reliable test methods furnish the designer with useful data and criteria for maximum utilization of filament winding.

References

1. R. W. Rosati, Public Relations Release, Olin-Mathieson Chemical Corporation, New York (March 1962).
2. A. J. Dervy, SPI Annual Reinforced Plastics Preprint, pp. 7D–1 (February 1962).
3. *Reinforced Plastics*, **2**, No. 3, 10 (1963).
4. E. D. Edmisten, *World Oil*, 91 (July 1959).
5. *Modern Plastics*, 94 (October 1961).
6. *Reinforced Plastics*, **2**, No. 3, 26 (1963).
7. A. G. Pehrson, SPI Annual Reinforced Plastics Preprint, pp. 2B–1 (February 1962).
8. *Reinforced Plastics*, **2**, No. 3, 28 (1963).
9. A. Griffith, Phil. Trans. Roy. Soc. (London), A221, 163 (1920).
10. E. B. Shands, *Glass Engineering Handbook*, p. 378, McGraw-Hill Book Company, Inc., New York, 2nd Edition (1958).
11. E. B. Shands, *loc. cit.*, p. 385.
12. E. B. Shands, *loc. cit.*, p. 414.
13. E. B. Shands, *loc. cit.*, p. 427.
14. R. E. Young, SPI Annual Reinforced Plastics Preprint, pp. 15C–1 (February 1958).
15. B. Levenetz, Narmco Research and Development Report W.O. No. 090–031, San Diego (December 1961).
16. W. J. Hamburger, Edgar Marburg Lecture, 58th Annual Meeting of ASTM (1955).
17. P. M. Goodwin, SAMPE *Meeting Report*, p. 384 (March 1961).
18. B. L. Duft, Narmco Research and Development Report, San Diego (May 1961).
19. *Missiles and Rockets*, **8**, 21 (1960).
20. H. L. DeBusk and W. R. McCarthy, *Product Engrg.*, **41** (1960).
21. L. L. Gilbert, *Missiles and Rockets*, **7**, 21 (1959).
22. Computer Sciences, Inc., Westbury, L. I., N. Y., to D. V. Rosato (personal communication).
23. Black, Sivalls and Bryson, Inc., Bulletin 45-110 (1961).
24. *Plastics World*, **21**, No. 4, 23 (1963).
25. *Plastics World*, **21**, No. 4, 25 (1963).
26. *Plastics World*, **21**, No. 4, 26 (1963).
27. *Plastics World*, **21**, No. 4, 27 (1963).
28. *Textile Organon*, **34**, No. 3, 35 (1963).
29. Plastic Report 10, Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, New Jersey, p. 1 (May 1962).

2 Applications

Within the past decade the applications of filament-wound structures have been many and diversified. The largest industrial product designed and manufactured with reinforced plastics is a filament-wound railway tank car with a capacity of 22,500 gallons. Commercial developments with production growth potentials are numerous and different, as shown in Tables 1.1 and 1.2. An example of a routine high-production item presently in existence is the high-voltage fuse tube.

Diversified applications which do not involve cylindrical or close-looped shapes include filament-wound springs and boats. Three years of service test on paper-making equipment springs have far exceeded the 6-month life for comparative steel springs. The superior energy-absorption characteristic of reinforced plastics has resulted in setting up service tests on truck springs and auto torsion bars. Developments are also presently being conducted to produce 14-feet long and 70-pound cartop wound boats (1).

A main effort of research and development programs has been directed specifically toward aerospace applications. Within this field, the major advances have been with rocket motors. The research and development conducted in these diversified fields were initiated principally to produce more efficient structures (2) and set up suitable winding machines.

It is estimated that the various designers and fabricators with filament-winding facilities have equipment investments ranging from one

hundred thousand to two million dollars. (See Appendix A for names of fabricators.) These include specialty organizations engaged in research and development, and also companies with large-volume production capabilities. Present indications are that at least eight million pounds of epoxies are being used for filament-wound applications. Mass-production concepts are being applied to commercial parts, since the basic finished cost for parts can be one dollar or less per pound (3).

STORAGE TANKS

The economic advantages of the filament-wound process have now started major development programs. This evolution is taking place in such major fields as containers. Large storage and processing tanks are being developed for chemicals, oils, and other corrosive products. Although their initial prices were about equal to those of lined galvanized steel tanks, the wound structures had the added advantage of lighter weight, less maintenance required, and outstanding corrosion-resistance performance. The present state-of-the-art is such that filament-wound storage tanks are being produced which are initially lower in cost (4), and they have been used by industry for the past few years to store acids, alkalies, chlorinated brine, salts, oils, etc. Table 2.1 lists the sizes of commercially available glass epoxy–filament wrapped tanks (5) for storing corrosive liquids. In Table 2.2 a cost comparison is made for 12,000-gallon tanks made of different materials.

Reinforced plastics is desired in corrosion-resistant storage tanks for fluoridation chemicals installed by water works. As cities adopt fluoridation of water, unusually strong materials are needed to combat

Table 2.1 "Poxyglas" Storage Tanks *

Tank No.	Capacity, barrels †	Diameter, feet	Height, feet	Approximate Weight
45-05-001-01	110	10	8	900
45-07-001-01	200	12	10	1,050
45-05-002-01	210	10	15	1,050
45-05-003-01	280	10	20	1,350
45-07-002-01	300	12	15	1,300
45-07-003-01	400	12	20	1,500

* Black, Sivalls and Bryson, Inc., Glass Fiber Products Division.
† 42-gallon barr ls.

Table 2.2 **Cost Comparison for 12,000 Gallon Tanks** *

	Poxyglas			Steel	
	Uninsulated	Insulated	Aluminum	304SS	Carbon
Tank thickness, inches	$\frac{3}{16}$	$\frac{3}{16}$	$\frac{1}{4}$	10 ga	$\frac{3}{16}$
Total cost, dollars	2,754	4,134	5,125	7,565	3,420
Tank cost, FOB fabricating plant, dollars	2,384	2,384	2,600	4,800	1,550
Insulation installed with water proofing, dollars	(4)	675	1,330	1,330	1,330
Heating coil, dollars (2)	(4)	705	705	705	250
Hook-up piping less control valves, dollars (3)	370	370	370	610	170
Pipe insulation, dollars	(4)	(4)	120	120	120

* Black, Sivalls and Bryson data, March 1963, with "Poxyglas" as the glass filament-wound tank and all tanks installed on a concrete pad and exposed to atmospheric conditions.

(1) Tanks assumed to be of equal high quality.

(2) 51 square feet of heating coil surface.

(3) Includes 100 feet of 2-inch-diameter piping made of same construction material as tank. Labor and material included in costs.

(4) In many Poxyglas tanks insulation not required because of the plastic insulating properties. Such applications include demineralized water, caustic soda, phosphoric acid, alum, corn syrup, etc.

the corrosive action of such chemicals as hydrofluosilicic acid. Tanks for storing 23 per cent acid are being made with glass filament–polyester resin composites.

Railway Tank Car

The largest industrial reinforced plastic or filament-wound item was recently made. It is a railway tank car 9 ft diameter and 55 ft long (6). (See Figure 1.1, page 4.) Total weight of this 22,500-gallon capacity tank with carriage is 26 tons. The basic weight of the tank is 8,000 pounds as compared with the 27,000 pounds for the steel tank it replaces. The plastic tank can contain 100 tons of liquid. Its working stress level is 12,000 psi at a 100-lb working pressure. This tank wall is $\frac{3}{8}$ inch thick. Its inside diameter is 100 inches at the ends and 103 inches at the center.

The inside surface of the glass roving–epoxy resin tank is completely covered with blue asbestos fiber–epoxy resin to provide maximum corrosion resistance (7). The plastic tank is initially less expensive than

aluminum, stainless steel, or lined-steel tanks. The inherent inertness to corrosion of the glass-epoxy composite makes it useful to transport many different corrosive solutions. Steam cleaning between different chemical loads is all that is needed to maintain the tank clean and in a corrosion-free condition.

A major design problem was to incorporate fittings, brackets, ports, and other attachment points. The final design eliminated these problems. Attached points were either wound into the wall reinforcements or attached to reinforced sectional openings. This procedure retained the structural integrity of the container, and the fittings were permanently located.

The glass-epoxy tank was manufactured by Black, Sivalls and Bryson, Inc., for the North America Car Corporation, Chicago, Illinois, who designed and assembled the finished railway car. This car was built primarily to meet the transportation problem, that is, to produce a larger and lighter tank for heavy and corrosive commodities. Weight alone of the conventional metal cars did not permit manufacturing a larger metal unit. The plastic tank with its 9-ton weight savings permits railroads to transport the corrosive liquids economically and efficiently. The plastic tank provides a higher payload-to-weight ratio and maximum corrosion resistance at a cost which is competitive to steel.

PIPE

The use of filament pipes in the oil-producing industry is another major application for filament winding. There have been extensive research and development programs for producing low-cost pipe. Filament tube and ducting which replaces aluminum units in buildings and in aircraft is another application. There is an expanding use in electric power poles for high-voltage transmission lines.

Pipelines have been used for many years to carry water, petroleum, and natural gas. Now their versatility is being exploited for purposes unsuspected by early users: to convey solids and to process products in transit (8). More than 453,000 miles of pipelines crisscross the United States, making them the third-largest freight carrier and supplier of more than half the nation's energy requirements.

The pipeline industry as we know it today actually started in the 1920's, when seamless and electrically welded steel pipe became available. Long pipelines, extending from 950 to 1,200 miles, were developed during the following decade, but it was not until the 1940's that

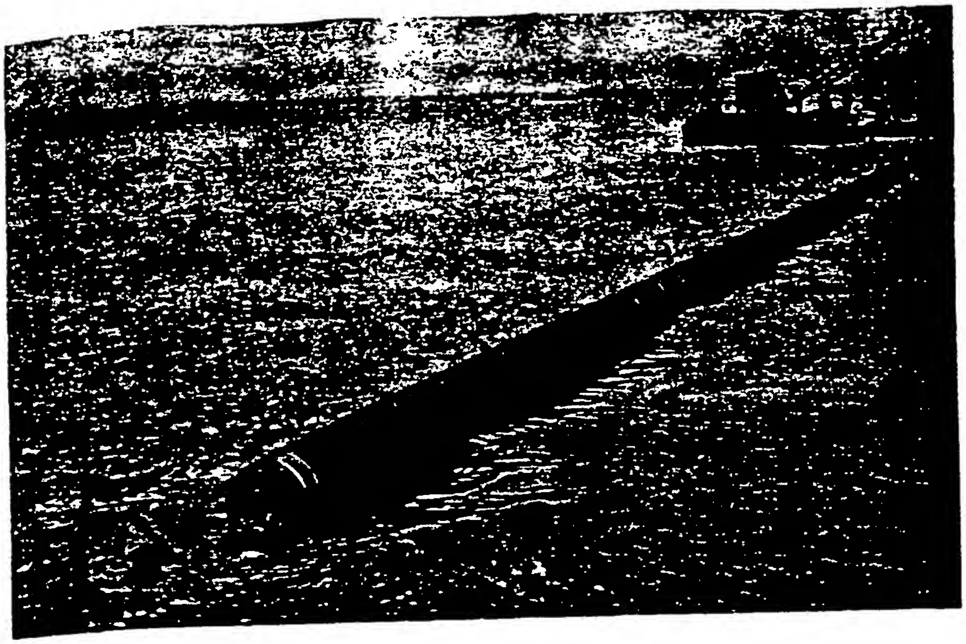


Figure 2.1 Installing waste pipe line which will be submerged in the Swedish West Coast salt water; glass roving-polyester tape wound tubes are coupled together underwater by frogman. (Courtesy of Hoganas-Billesholms A B, Sweden.)

pipelines really made their major contribution. In the 1950's, developments in glass filament–epoxy pipelines were initiated.

Glass-epoxy pipe for salt water gathering and disposal systems, gas gathering and water flood systems, etc., are now available at less cost than protective steel. Miles of pipe have been installed with no bulky, expensive equipment required in laying. Bell and spigot coupling in 30-foot lengths have been principally used in order to produce quick installations (9).

Almost eight years of intensive laboratory research and field testing have produced commercially competitive and efficient pipe. Precision-controlled equipment produces maximum strength in both the hoop and axial directions of the pipe. Commercial pipe 30 feet long is now available in diameters ranging from 1 to 12 inches. Larger diameters are available on special orders.

Constant operating temperature for the filament-wound pipe is 150°F, though pressure ratings are maintained at surge temperatures up to 300°F. Rated pressures are 300 psi for the 2-inch, 225 psi for a 3-inch, and 150 psi for a 4-inch or larger diameter. Proof tests are conducted at pressures four times greater than their psi ratings. The

commercial pipe can withstand pressures of up to approximately ten times its rated capacities when tested to failure.

A continuous method for the production of glass fiber–reinforced polyester pipe with diameters up to 60 inches is being used. Interesting applications include pipelines for corrosive liquids and submarine pipelines or ventilation pipes specifically for corrosive conditions. One of the manufacturing techniques uses roving glass cloth, impregnated with catalyzed polyester resin. It is wound on a short rotating mandrel and continuously pulled along and off the mandrel through a curing oven. The impregnated roving cloth is cured in the oven and is removed from the mandrel while it is rotating (10).

The production is normally adjusted for a standard tube length such as 12 feet. The advantages of the process are that the cost for labor is extremely low, only one mandrel for each diameter is necessary, and heat consumption for curing the pipe is low. Heat consumption is low because the mandrels are kept at a constant temperature, and there is no need for cooling and reheating mandrels.

Tubes with different wall thicknesses can easily be made, and reinforcing materials other than glass cloth can also be used (asbestos fabrics and felts) (11). The continuous manufacturing process leads to a lower production cost. By using different types and amounts of reinforcing material or resins, it is very easy to develop different properties in the pipes.

In addition to glass-reinforced pipe a line of asbestos-reinforced resin pipe and fittings exists. Early attempts at producing asbestos-reinforced thermal-setting resin pipe resulted in structures which were porous and caused weeping when moderate internal pressure was exerted (12).

Asbestos-reinforced thermosetting epoxy or phenolic resin piping and fittings which do not weep are now available. The asbestos fibers used are specially prepared and converted into highly saturable asbestos papers or felts. The impregnated sheets are converted into varying lengths of pipe by being wrapped on a mandrel under heat and pressure. Curing is performed in an autoclave at 100 psi and 338°F for 2 hours. The pipe is then stripped from the mandrel and postcured for 4 hours at 400°F. The piping materials are homogeneous throughout the wall and contain no liners to resist the action of fluids. The minimum resin content of a pipe is generally 50 per cent, which is somewhat above the minimum value necessary to produce a void-free material. Field tests of at least 5 years have indicated no failures due to weeping (13).

A comparison of pipe materials shows that reinforced plastics have

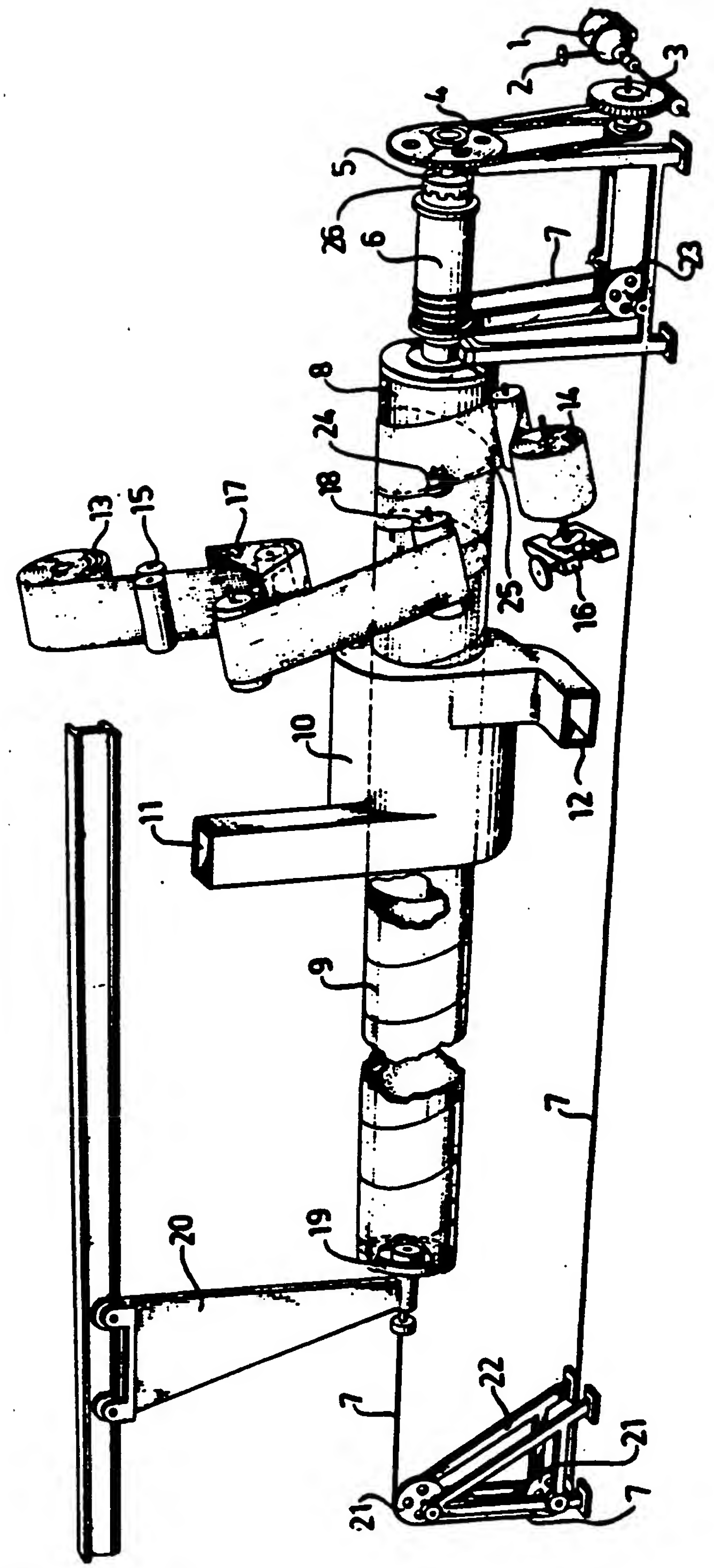


Figure 2.2 Tape wrapping schematic of a tube-making machine. (Courtesy of Hoganas-Billesholms A B, Sweden.)

weight and cost advantages compared to those of metal pipe. In an 1,800-foot installation of 6-inch filament-wound pipe for use with cupric, cuprous, and ferric sulphate mine water, the plastic pipe weighs 10,000 lb and costs $29,000. For rubber-lined steel pipe, weight is 58,000 pounds and cost is $27,500. Installation cost of the heavier pipe is much higher, so that the total cost of the plastic pipe and installation is lower than the steel.

AEROSPACE

Because of the extreme performance penalties exacted by even small increments in the weight of a space vehicle, the major challenge continues to be to develop the most efficient strength-to-weight ratios in aerospace structures. The use of filament-wound reinforced-plastic systems has been found to be a particularly advantageous way of determining the structural capabilities of many types of space-vehicle components.

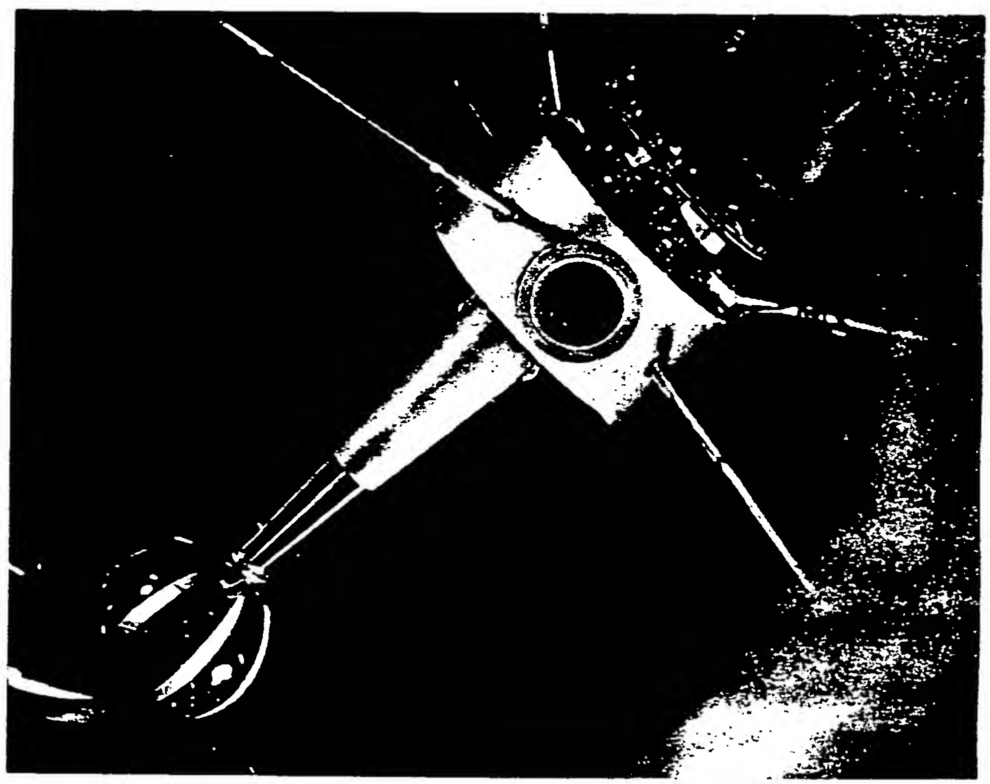


Figure 2.3 Filament-wound pedestal and ball for space shot. (Courtesy of Lamtex Industries, Inc.)

In a multitude of space applications, reinforced plastics have already proved to be an apt answer, not only to purely load-carrying requirements but also to a diversity of problems relating to thermal barrier and electronic applications where strength considerations are important (14). Recorded successes of plastic composites in space applications are reported. Assuming that methods can be developed to restrict long-term radiative deterioration of reinforced-plastic materials, and noting the accelerated rate at which improvements have been achieved, it becomes obvious that more wound applications will be developed for the future (15). Existing reinforced-plastic systems have already provided the best available solutions for many severe problems of space-age materials, heat shield, power-source packages, antennas, and structural spheres.

For a lunar probe, it is possible to make the entire vehicle of reinforced-plastic material. This includes a retro-rocket as well as the vehicle that will traverse the surface of the moon. The moon vehicle is designed to land on the retro-rocket. These rockets can have circular corrugations to absorb part of the shock of impact (16). The weight saving gained by fabricating the vehicle from wound material plus the advantages of shock absorption are important factors to be considered (17).

The Ranger spacecraft lunar-landing capsule includes a filament-wound case and nozzle motor assembly. This retro-rocket motor case with nozzle weighs only 15 lb. The total weight of the lunar capsule is 325 pounds.

MISSILES

Filament winding has been applied to different development and production missiles including the Arcas; Argo D-4 and D-8; Atlas—Able I, II, III, and IV; Bolt; Bomarc; Caleb; Deacon; Delta; Discoverer; Javelin; Jupiter; Minuteman; Mercury; Navaho; Nerv; Nike-Zeus; Pershing; Polaris A2 and A3; Ranger (18); Scout; Shot-put; Talos; Terrier; Thor—Able I, II, III, and IV; Tiros; and Vanguard. Applications include solid rocket motors (19), liquid engine containers, nozzles, exhaust cones (20), heat shields, nose cones, blast tubes, electrical conduits, electronic containers, and radomes.

It is interesting to note that advancing the state-of-the-art in building rocket motor bodies was a natural development of filament winding. In many of the previous developments that used reinforced plastics, disadvantages and cumbersome obstacles were found to exist. It has been predicted that within the next decade, solid rocket motor

cases, regardless of size, will be predominantly filament-wound. In addition to performance efficiencies, there are sizable cost advantages (Table 2.3).

The rocket casing used in the advanced solid propellant design is essentially an optimized pressure vessel. It is under static internal pressure and dynamic and/or thermal loads during its flight. In the past, consideration of internal pressure was the primary structural requirement.

Recent applications for motor cases in the larger rockets such as the Minuteman ICBM measuring up to 5½ feet in diameter by 24 feet in length have resulted in other major structural requirements (21, 22). Today propellant tanks are generally required to carry handling and erecting loads, axial loads, and bending loads caused by wind on the launcher, actual thrust control loads, and wind shear bending loads in flight.

Fabrication techniques begun approximately a decade ago involved winding diameters up to 54 inches. Skirt attachment shoulders were included in the rocket chambers. The latest target is for 120-inch, 156-inch, and 260-inch diameter by at least 40-foot long solid booster cases for missiles such as Titan III (23). These large glass-wound cases are being developed to produce 2,500,000 pound thrust boosters. Future targets involve diameters of 380 and 540 inches. In addition to these costly development motors, major efforts are being made by agencies such as the National Aeronautics and Space Administration to develop low-cost mass-produced units. An example is the development of the filament-wound, improved, fourth-stage "poor man's" Scout research rocket (24).

Solid-fueled rockets with extremely good overall performance have been developed. Such performance is a direct result of the filament-wound cases employed. These types of motors, when used as an upper

*Table 2.3 Comparative Costs of Glass-Filament-Wound and Metal Rocket Motor Cases **

Material	Dollars/Unit	Tooling Cost, dollars
Glass fiber/epoxy	13,000–20,000	100,000
Steel wire/epoxy	12,000–20,000	100,000
Steel	40,000	600,000
Titanium	60,000	600,000

* Bas d on production lots (14)

stage of a space vehicle, will allow a significant increase in the weight of the payload to be put in orbit around the earth. They derive their performance from the combination of a high-energy solid propellant, advances in design techniques, and the application of lightweight insulation with glass fiber materials. For example, a new motor 7 feet long and 2 feet in diameter containing 850 pounds of propellant produces a specific impulse of 275 under space conditions. Mass ratio or the ratio of the weight of the propellant charged to that of the casing and other hardware is 0.94. Thrust is 6,000 pounds for more than a half a minute (25).

In practical demonstrations, large, segmented, filament-wound motors have been successfully fired with a 12,000-pound thrust using 3-segment rockets. Walls were cold to the touch after a 120-second test run. These test engines measure 5 feet in length by 2 feet in diameter (26).

Another development has been the production of lightweight, filament-wound, ablative-cooled thrust chamber assemblies for liquid-fuel rocket engines capable of withstanding extended firing durations. A 2,200-pound thrust engine using this type of chamber has been continuously fired for 4.5 minutes. The engine achieved duration of 7.2 min with refiring. Unlike the thrust chambers of regenerative-cooled engines, this type of ablative-cooled chamber requires no expensive tubing. It is simple and reliable and has a relatively low production cost. It also has restart and throttlability characteristics.

This type of design permits changes in nozzle dimensions which can be predicted and controlled within acceptable limits. The thrust chamber assembly can be used in engines of both low and moderately high thrust. Firings can range from a small 100-pound thrust engine suitable for Vernier control, mid-course guidance, and orbital correction to engines large enough for the main propulsion of the upper states of space vehicles. The chambers use a protective liner of ablative material which slowly liquifies and vaporizes, removing heat and providing an effective insulation of the engine's structural shell (27, 28). The combustion heat of the chamber is effectively rejected by the slow, controlled removal of the ablative liner material (29).

A relatively new approach is that of filament winding a motor case directly on the solid propellant rocket grains. In this process, the propellant grain, insulating components, and end closures are wound as an integral unit. Important technical and cost advantages are realized by this technique. However, one of the prime disadvantages is the hazardous nature of the winding operation. Programs have been proposed whereby the solid propellant can be cast and filament wound at the launching site.

Another interesting application for filament winding in rockets is the consumable motor case. The consumable case rocket has a 40 per cent greater than metal type of earning velocity and a nominal burn-out mass ratio of 30. This type of case behaves like a continuously jettisoned unit.

Polaris

In part, the accelerated effort to extend the range of the Navy's Polaris is being answered by rapidly extending filament-wound case capabilities. The push to produce Polaris A3 with a range of 2,500 miles has resulted in a 30 per cent gain in the operating stress level of glass-fiber motor casings. Steel was used for both stages of the 1,200-mile-range Polaris A1 now deployed aboard operational submarines. The 1,500-mile Polaris A2, now entering production, is a hybrid with a steel first stage and a fiber glass second stage (30).

Both stages of the A3 use filament-wound cases. The two principal advantages of glass over steel are a substantial weight reduction and a 66 per cent cost reduction. The A3 is scheduled for operation early in 1964.

In addition to the lightweight casings, objectives in the A3 program are development of a hotter propellant, with a major increase in specific impulse, and reduction of component weight through miniaturization. The A3-range extension is to be achieved within the dimensions of the A2 missile, namely, 31 feet in length by 54 inches in diameter (31).

These new requirements have resulted in major materials research and search for new methods of studying the resistance of motor cases to fracture failure, by debonding of joints or laminations and by splitting fractures in the glass fiber hoop windings (32). Nondestructive and flaw-detection techniques are being advanced, but the correlation of irregularities and defects with expected performance is only beginning. Developments continue to result in new instruments for the detection of moisture in the composite (33).

Minuteman

In 1960 the awarding of production contracts for both Minuteman and Polaris upper stages to fabricators of glass epoxy-wound structures provided a real boost to the winding industry. Cost savings of 90 per cent occurred in filament third-stage case development in the Minuteman when they replaced titanium cases (34, 35).

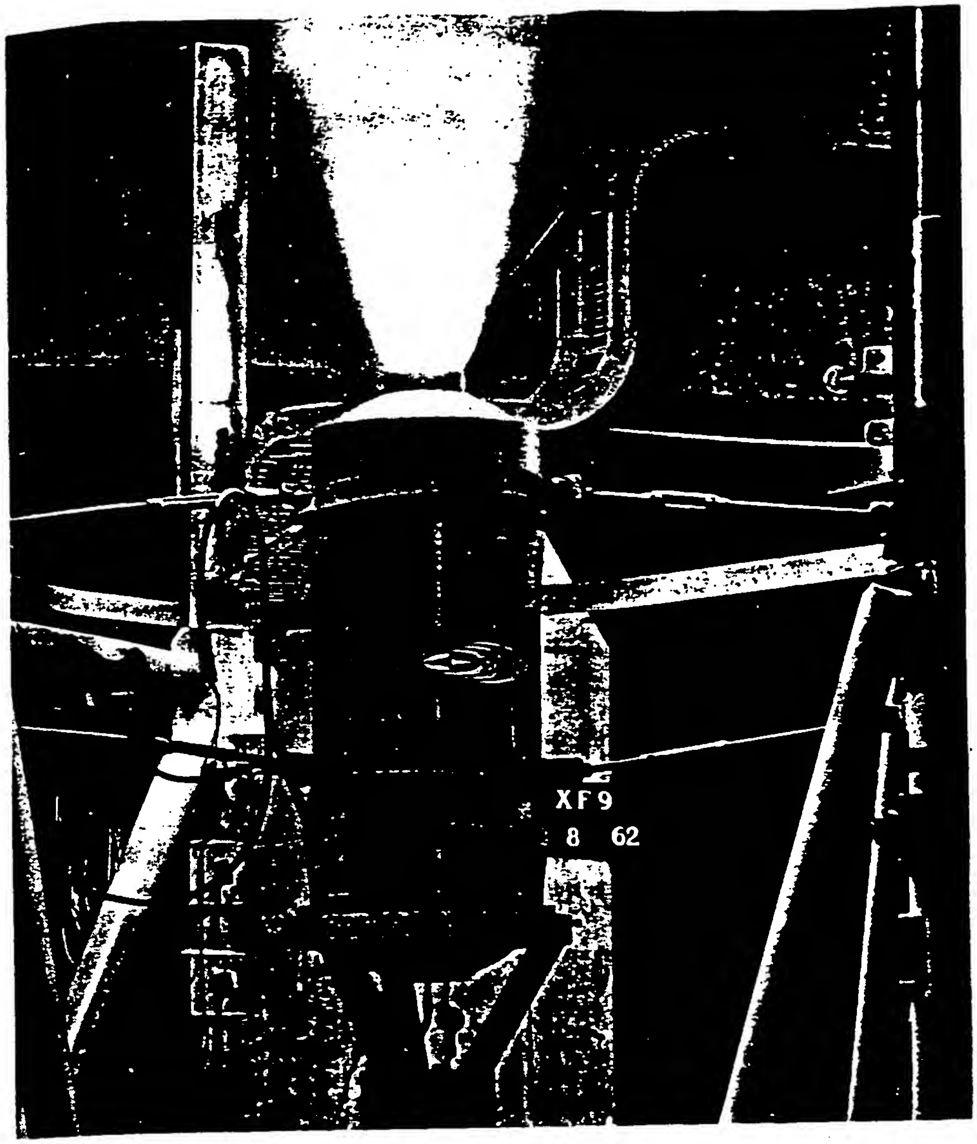


Figure 2.4 Three-segmented, solid propellant glass-fiber rocket motor being test-fired. This type of casing provides a means for developing low-cost, lightweight, large solid boosters. (Courtesy of United Technology Corp.)

Studies are presently continuing to produce full-scale cases for the first and second stages of the Minuteman missile. The case developments include the design of skirts, blast tube, and winding mandrels and establishment of design allowables. Skirt designs have been evaluated for structural integrity, reliability, strain compatibility, cost, and ease of fabrication. Among the various designs considered were one-

piece steel, metal fiber glass laminates, all-glass reinforcement with metal bushings at attachment points, and nonferrous all-metallic. After extensive analysis, it was determined that the all-reinforced plastic skirt with metal bushings at the attachment points would be most desirable from the standpoints of handling, compatibility, cost, and coefficient of expansion compatibility characteristic (36).

Atlas

Weight reductions have been quite substantial in the predicted production of the Atlas rocket motor since filament-winding procedures were adopted. A 25 per cent weight reduction has already been achieved. The previous method used steel restraining bands around the combustion chamber of the engine. This saving, which amounts to approximately 56 pounds, could be increased by further reducing the amount of winding used. Cost savings are also in the neighborhood of 25 per cent.

The process involves winding a glass-filament roving impregnated with an epoxy resin around the combustion chamber. Longitudinal sections of tape or similar material are also used. The tape is loosely woven roving with a minimum of cross filaments. When applied to the Atlas chamber, and varying case wall thickness, the material averages approximately $\frac{3}{16}$ inch in thickness. Curing is accomplished in an oven at 200°F to 300°F in 2 hours (20).

Pershing

Although the Pershing rocket motor case is a plastic-covered aluminum structure, cost estimates have indicated that a cost saving of $20,000 per case could be realized if the case were made of glass-filament-wound plastics. The function of the ablative plastic and the structural aluminum can be assumed by the filament-wound plastic (37).

Pressure Vessels

Filament winding of rocket motor and nozzle casings for operational use is relatively new. The use of filament-wound pressure vessels for high-pressure gas storage dates from 1950. Filament-wound spherical storage bottles have been used on a variety of rocket vehicles for approximately four years. Usage has been even greater on manned military aircraft for approximately six years (38).

Experience with filament-wound spherical pressure vessels has been accumulated. Some of this experience can be applied to the newer filament-wound structures now going into service. The earliest glass fiber vessels to be placed in operational service were for the F-84F airplane. Later spheres were also put into operational use for the F-102 and F-106 airplanes. The service pressure for these storage bottles was 3,000 psi.

Glass-wound pressure bottles are used around the top of the Saturn superbooster. Fifty-one bottles are used to apply pressure in the large fuel tanks in order that fuel can be pumped into rocket engines during flight.

Jato Motors

Jet-assist take-off units (Jato) are used for rapidly ejecting aerospace vehicles. Filament-wound units which can meet standard homogeneous metal Jato requirements and are lower in weight and price are being produced.

The first of these units were 9 inches in diameter by 27 inches in length, with a burning time of 14 seconds. They were hydrostatically pressure tested at 3,000 psi. Advanced designs in solid propellant gas-generator units for aerospace vehicles incorporate filament-wound spherical containers (39).

HYDROSPACE VEHICLES

Filament-wound underwater structural hulls are being developed specifically for operations down to 20,000 feet in depth. New advances in oceanographic studies are requiring the applications of structural materials such as filament winding. This is potentially a large field of endeavor, for the oceans cover 70 per cent of the earth's surface. In turn, 70 per cent of those oceans lie between 10,000 and 20,000 feet in depth (40).

Deep-submerged pressure hulls can be officially designed and fabricated using filament-wound structures. Concentrated research and development programs using filament-wound structures in hydrospace vehicles was recently initiated. Wall thicknesses of up to 12 inches are being considered. These programs simulate previous programs of aerospace development concerned specifically with rocket motors. Extensive exploration of our oceans requires more efficient structures for depths below 400 feet. Torpedo hulls are being redesigned to utilize wound units in solid or sandwich construction. These types of

structures are also being used as combination power-source containers and hull structures (41).

Vessels Subjected to External Pressure

Most of the development of filament-wound and all-metal structures for containers has been specifically concerned with internal pressure applications. Very limited data are available on containers subjected to high external pressures (42).

Underwater development programs have indicated the desirability of applying filament-wound structures in low-depth operating hulls. Basically, deep-submersible structures are pressure vessels with directional stress requirements (43). A filament-wound construction provides an almost 100 per cent efficient strength-to-weight structure. With homogeneous metallic materials, additional weight must be incorporated in a structure to satisfy a load requirement in one direction only. This type of structure is only partially utilized in other directions. Experimental testing conducted on glass filament-wound structures demonstrates definite potential advantages over metals (41). Test data on actual models agree with the pressures computed from formulas based on thin-shell theory considerations for isotropic materials.

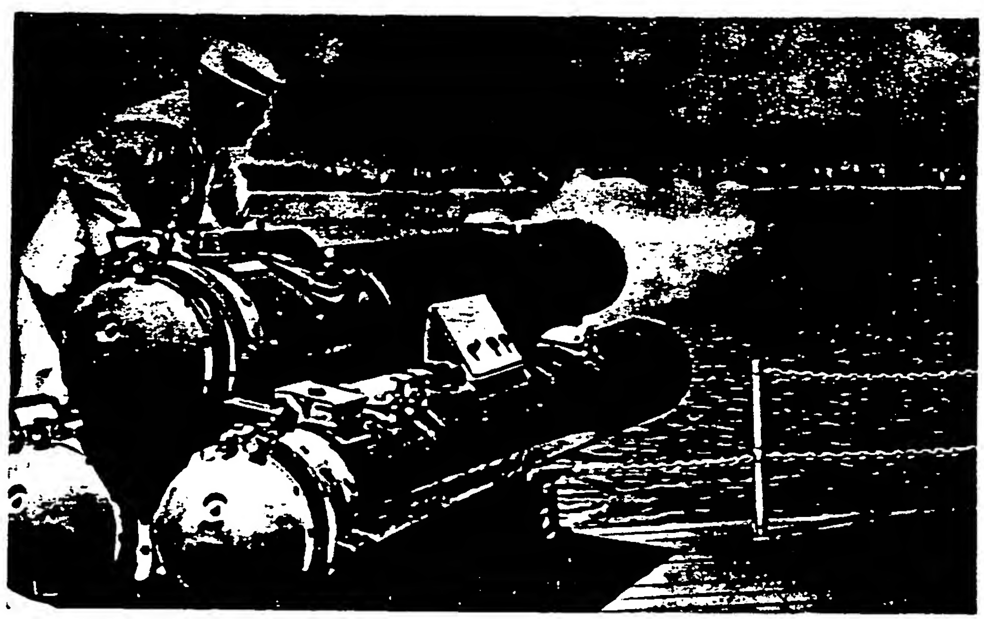


Figure 2.5 Torpedo launching tubes. (Courtesy of Hooker Chemical Co.)

Ideal characteristics for metals in pressure-hull applications have been summarized (44). These characteristics for hydrospace vehicles are as follows:

Density	As low as magnesium (0.065 pounds/cubic inch)
Yield strength	300,000 psi
Moduli	Tension 40×10^6 psi, shear 15×10^6 psi
Toughness	Will not fracture in a brittle manner under severe plastic deformation at 0°F or lower.
Weldability	95 per cent joint efficiency or greater in as-welded condition for yield strength, toughness, and fatigue strength.
Formability	Hot-formed or cold-formed to shape, without needing subsequent heat treatment.
Repairable	Weld repairable under service conditions.
Fatigue	Notched fatigue strength of welded structure at least 90 per cent of unnotched fatigue strength of basic material for low-cycle, high-stress, and plastic-strain conditions, in which number of peak stress cycles is 20,000 or less.
Corrosion	Not susceptible to stress corrosion. Corrosion-fatigue strength equal to air-fatigue strength.
Stability	Will not creep or change dimensions significantly under operating stress (75 per cent of yield strength).
Isotropy	Mechanical properties identical in any plane.

Note that by virtue of their density, strength, and modulus, glass-filament-wound structures are tailor-made to meet these requirements. The filament structure can be designed to meet preferred strength directions. Other favorable properties of these filament materials are their availability, formability, and nonmagnetic characteristics. Design concepts utilizing different types of filament-wound materials have been theoretically evaluated and compared with limited experimental substantiation. Design concepts under study include sandwich-constructed directionally wound shells, ring-stiffened directionally wound shells, and unstiffened directionally wound shells (41).

This study was based on different diameters of approximately 6¼ and 144 inches, with an approximate length-to-diameter ratio of 1.5. The weight ratio for the sandwich and the unstiffened shell shows little change for the two diameters based on the same strength level. However, the ring-stiffened shell becomes more efficient as the diameter increases.

In sandwich construction, the stiffening effect is derived from an increase in the core depth. In ring-stiffened construction, the effect is derived primarily from ring spacing, which becomes structurally more efficient in larger diameters. At moderate ocean depths, the thinner facings in a sandwich cylinder wall necessitate a greater total wall thickness (increase core thickness) in order to satisfy the buckling criteria. The thinner shell for a ring-stiffened cylinder wall requires that the critical length between the rings be smaller to satisfy the buckling requirement. Theoretical data indicate that for ocean depths to approximately 30,000 feet the sandwich or ring-stiffened shell would be most efficient on the basis of the weight ratio. In the case of a high strength level and small diameter, the sandwich wall construction concept is more efficient than the ring-stiffened shell concept.

In order to develop desirable sandwich structures, basic and applied development of the base material used and the methods of fabrication is required.

Theoretical calculations indicate that for depths below 30,000 feet a solid wall is most efficient. When considering a sandwich structure below these depths, the skins of the sandwich are excessively thick, so that the theoretical core thickness approaches zero.

Boats

The use of conventional reinforced plastics in boats has become a major and large business. The use of the material is so extensive that on certain boats only the engine marine hardware items and mechanical fasteners are made of metal.

Glass-filament-wound parts are being applied where basically structural, special requirements and/or production cost advantages exist. Examples include masts, antenna tubes, vent cowlings, chemical storage tanks, and battery containers. An interesting development at present involves fabricating wound 14-foot-long cartop boats, which weigh 70 pounds. The program is to produce cost-competitive durable boats, principally to replace aluminum boats.

GUNS

Shotgun Barrel

The new barrel in the Winchester Model 59 semiautomatic shotgun is considered the first innovation in barrel design in half a century.

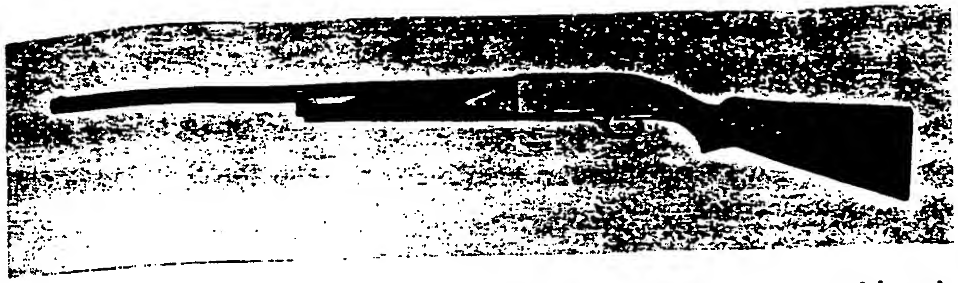


Figure 2.6 New Winchester Model 59 automatic shotgun with glass wound barrel. (Courtesy of Olin Mathieson Chemical Corp.)

Developed and placed on the market after five years of research, it introduces a new application for filament-wound structures.

The new barrel, called the "Win-Lite," provides the following advantages (45).

1. *Durability.* The barrel and receiver cannot rust, rot, or be affected by exposure to weather.
2. *Added safety factor.* Research and field tests show that the glass fibers provide a barrel with greater burst strength than steel.
3. *Cooler shooting.* The heat-absorbing qualities of the glass fiber eliminate hot barrels and heat-wave distortion, making a ventilated rib unnecessary.
4. *Faster pointing.* The weight reduction in the barrel permits faster pointing.

The history of firearms and barrels which have resulted in a filament-wound barrel is also the history of man's advancement in the technological arts. In the middle of the fourteenth century when firearms became commonly used, the art of metallurgy was in its infancy. The poor quality of the metals then available required that firearms or artillery pieces have massive walls to contain even the low black-powder pressures encountered. Even so, the probability of a burst was so great that often condemned prisoners were made to do the firing and were restrained from escaping by armed soldiers.

During the second half of the fifteenth century, metallurgy had improved and hand guns became quite common. By that time, means had been found to hammer and heat-weld flat strips of wrought iron along a mandrel to form the bore of a gun. This type of construction persisted well into the Machine Age, when it became possible to form the bore of a gun by drilling or boring solid stock. An improvement on the basic method of welding strips of iron together was demonstrated by the famous Damascus barrels, in which the strips

of metal were alternately soft iron and steel. The strips were wound spirally around the mandrel.

It was not until about 1840 that the Whitney Arms Company first used steel in barrels. Even then, the quality of the steel was such that barrel walls were massive and an octagonal construction was used to obtain maximum strength with the least possible weight. In the 1890's, smokeless powder began to be used and steel barrels were a necessity since the old Damascus barrel would no longer contain the pressures involved.

Late in the 1890's Winchester started using nickel-alloy steels for barrels. The basic design of these barrels has persisted with very little change up to the present time.

Over a period of some 300 years, a gradual improvement of materials of construction allowed firearms to become less massive and easier to handle and carry. For the past 60 years, there has been no basic change in the design of barrels, particularly for shotguns.

The Win-Lite barrel is considered a major change. It is comprised essentially of a cylindrical thin-metal liner and a surrounding glass-resin-wound structure. It is made by a process which is a throwback to the old technology of winding a barrel with strong steel wire to increase its burst strength. Instead of steel wire, glass fibers are used. Manufacturing begins with the cylindrical liner, which is made from seamless drawn-steel tubing with a wall thickness of only 0.020 in. A high bore polish is then evolved through conventional microhoning operations. Conventional barrel-making techniques are also employed to provide a threaded end section of chrome-molybdenum steel alloy. Use of steel at this point is required for assembly and disassembly of the barrel to the gun action.

Once the liner is completed, it is wound with glass filaments (10 ends of 150 1/0 strands), which are pulled from a creel under controlled tension, passed through an epoxy-resin bath, and wound by rotation of the barrel. The contour of the barrel is essentially shaped by this winding process. Epoxy resins have been developed specifically to provide a material whose properties can be varied with hardness or elastic characteristics. The resin system also provides an exceptional high-strength bond to the steel core.

After the assembly is oven-cured, the barrel is sanded lightly to provide a roughened surface for the final application of glass fabric tape. At this point, the gun barrel has an exceptionally high burst strength. However, it also has a deficiency, namely, a tendency towards longitudinal whip. In order to overcome this problem and

attain the rigidity needed for good accuracy, unidirectional glass cloth tape is applied so that the lengthwise fibers lie parallel to the longitudinal axis of the barrel. The tape is wrapped dry. In order to obtain a tight wrapping, an expendable cotton gauge is wrapped around the glass tape.

After being wrapped, the barrel is oven-dried and then impregnated under a relatively high vacuum with a modified epoxy-resin system. The impregnated barrels are again oven-cured before being ground to finished contour. The holding lug and front sight are bonded on the plastic barrel with a heat-cured epoxy adhesive. The barrel is given a final spray finish of a prime coat and finish coat of baking-type materials formulated with epoxy resins.

In test firing of thousands of rounds, the Win-Lite barrel has been found to be stronger and more durable than any steel barrel. As an indication of its strength, a 20-gauge shell was dropped in a Win-Lite barrel ahead of a 12-gauge shell and the gun fired. The result of this test showed that the barrel was unaffected and could easily withstand the tremendous pressures. Any barrel can be burst by putting into the bore a sufficiently heavy obstruction. But rigorous testing has indicated that bore obstructions sufficient to bulge or burst a good steel barrel will cause the filament-wound barrel only a slight ring, which is barely noticed and which does not impair the shooting characteristics of the gun.

While some all-steel barrels could conceivably be used as crowbars, the filament-wound barrel could not. The plastic barrel has been designed to give added advantages in shooting and to keep the sportsman from having to carry around extra weight. Crowbar strength is not built in, but safety in shooting is included. If bent, the barrel can be straightened without cracking or chipping.

A finish is used that has been highly tailored to have the appearance, flexibility, and weather resistance demanded of the best gun barrels. It will not rust, fade, or discolor, and it will not be affected by any gun oil, bore cleaner, or other preparation.

The heat and cold characteristics of the plastic barrel are radically different from those of a steel barrel. In cold weather, the barrel will not cause frostbite on the hands. At the other extreme, after a fast round of trap shooting the barrel can be handled without any danger of getting burned. The principle of the nonrecoiling barrel reduces recoil to a bare minimum even in the lighter gun. Recoil is a soft, steady push, rather than a sudden jab, with a measured 20 per cent reduction in recoil effect.

Rec il-less Rifle

Feasibility studies have been conducted in the design, fabricating, and testing of epoxy-glass, filament-wound, hand-operated recoil-less rifles. The plastic rifle has the advantages of light weight, high strength-to-weight ratio, ease of handling, and relatively low cost. The materials and manufacturing process are low in cost. Another very important characteristic of plastic rifles compared to metal counterparts is that the plastic rifle provides a transparency characteristic which lends itself very effectively to the observation and study of propellant initiation and combustion phenomena (46).

The initial phase of this development program involved the design of suitable mandrels. Aluminum mandrels were used which were machined to a 32-surface finish. Before the start of the winding operation, the mandrel was coated with three thin coats of trichloroethylene (DC 20). Epoxy resin with 12-end glass fiber were used. The number of layers of fiber and the pattern of wrap used were determined on the basis of stresses acting on the system.

A total of 67 layers of hoop (circumferential) winding and 18 layers of helix (longitudinal) windings were applied under constant filament tension. The actual layup was 20 layers of hoop, 9 layers of helix, 20 layers of hoop, 9 layers of helix, and 27 layers of hoop. Several additional layers of hoop were then added to permit machining of the outside diameter of the rifle to meet its final required thickness. The inside of the tube was not machined, since it was not necessary. Parts were cured 2 hours at 100°C and for 12 hours at 200°C.

Dry ice was placed inside the mandrel in order to remove the cured shrunk filament-wound structure. Since the thermal contraction of aluminum is approximately twice that of the plastic, separation could be made with the cold environment. The glass content of the cured part was approximately 85 per cent by weight.

Some delamination of the inside layer of hoop windings occurred during firings. This problem can be remedied by using an inside liner made of erosion-resistant metal or asbestos. Another remedy could be the utilization of helix windings on the inner surface in place of hoop windings.

The hoop-to-helical ratio used was 4 to 1, since there was an open-tube load requirement. In a closed pressure vessel, the stress induced in the hoop direction is twice the stress in the longitudinal direction. Results of actual firings with the plastic rifle indicated that the longi-

tudinal strain output was too low to be measured. It therefore appeared feasible to reduce the number of low lead helix windings.

This plastic unit provides high strength-to-weight ratio and in addition can absorb large amounts of energy. A 150 to 200 per cent increase in strength owing to dynamic loading can be expected.

Artillery Shell Grommet

Grommets for use in shipping and storing artillery shells have been investigated by the military. They are used as protection for the soft-metal rotating band of artillery shells. The previous conventional grommet in use was fabricated of painted steel with a paperboard liner and held in place with steel wires twisted together. The disadvantages of the metal type are that it is subject to denting or rusting, wire tends to loosen or break, and application to the shell cover is cumbersome. Conversion to polyester or epoxy-glass-wound combinations eliminates corrosion problems. In addition, a unit can be designed that will simply slip over the shell and hold itself in place by its integral resiliency. Although the initial cost of the filament-wound grommets is slightly greater than that of the existing units, the problem of reducing maintenance results in overall cost reduction. The maintenance-free characteristic of glass-filament-wound structures has resulted in the reduction of long-range cost figures.

ELECTRICAL EQUIPMENT

Switch gears, high-voltage fuse tubes, circuit breakers, high-voltage insulators, etc., are made with filament-wound tubes which have high burst strengths and the usual plastic nonconductive electrical characteristics. Diversified electronic applications include wound lamp posts and truck-mounted booms. These man-carrying booms are used in utility repairs or for tree surgery (3).

Resin-impregnated unidirectional glass tapes have found many and varied uses since their development. One of the first rigorous technical applications for such materials was in binding down the windings of rotating armatures of electrical equipment. It was natural for glass banding to find application, since it is a nonconductor and nonmagnetic and has a high strength-to-weight ratio, a low modulus of elasticity, a low coefficient of thermal expansion, and a low creep rate. It has been replacing steel wire on end bands, slot wedges on armature cores, and clamp rings in commutator construction.

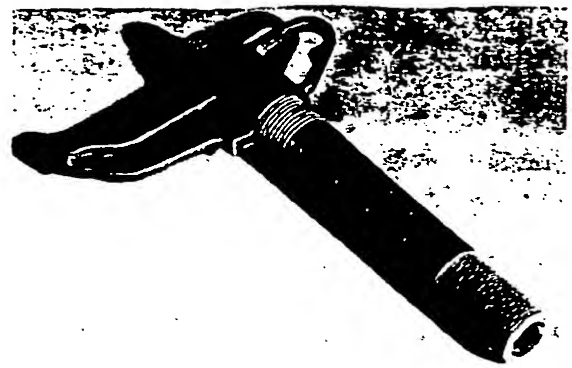


Figure 2.7 High voltage fuse cutout assembly: machined threaded glass wound 1⅛-inch. O.D. tube has static burst pressure of 50,000 psi. (Courtesy of Spaulding Fibre Co., Inc.)

In rotating electrical equipment there is concern with containing armature windings and commutator segments against the centrifugal effects of rotation. There are two ways this can be accomplished. One technique is the so-called brute-force method, and the other is the shrink-ring method. In the brute-force method there is no prestressing. Sufficient restraining material is applied so that rotational stresses and therefore radial movements are kept within acceptable limits. The shrink-ring method involves prestressing a shrink-ring (or band under tension) so that radial movement is significantly reduced until this prestress is exceeded.

The effect of temperature in these systems has a significant effect on the application both during and after curing of the bands. During the application and cure of the bands it affects how much strain can be retained. After cure of the bands heating of the system during operation is important, for it affects the heat-aging properties of the material and the tightening or loosening of the band caused by its thermal expansion in relation to that of the substructure. In general, the coefficient of expansion of the glass band is less than that of the substructure, so that a tightening of the band occurs during elevated temperature exposures (47).

AIRCRAFT

The aircraft industry has been applying the reinforced plastics in its aircraft structures, principally to reduce cost and weight. Low-cost filament-wound monocoque structures are presently being investigated. Conventional glass-reinforced plastic parts now being

used for aircraft such as the commercial and military jet liners include rudders, vertical stabilizers, radomes, trailing edges, air ducts, and liquid containers. Filament-laminated undercarriages for light airplanes have been developed and are now in production. They provide better shock-absorbing and dampening properties than conventional undercarriages, and they minimize bouncing (48).

Filament-wound radomes have been fabricated for high-speed aircraft. In this application, the conical radome is tailor-made for the winding process. Radomes made with glass roving–epoxy materials provide the desirable electrical transmitting properties and a high strength-to-weight ratio (27, 49).

PRODUCTION FORECAST

In 1962 the United States Department of Commerce reported a total USA plastic materials consumption of 7.3 billion pounds. Industry projected forecasts for 1967 and 1975 are 12 and 18 billion pounds, respectively. Since 1950 reinforced plastics consumption has been approximately 4 per cent of total, or 290 million and 480 million pounds in 1962 and 1967, respectively.

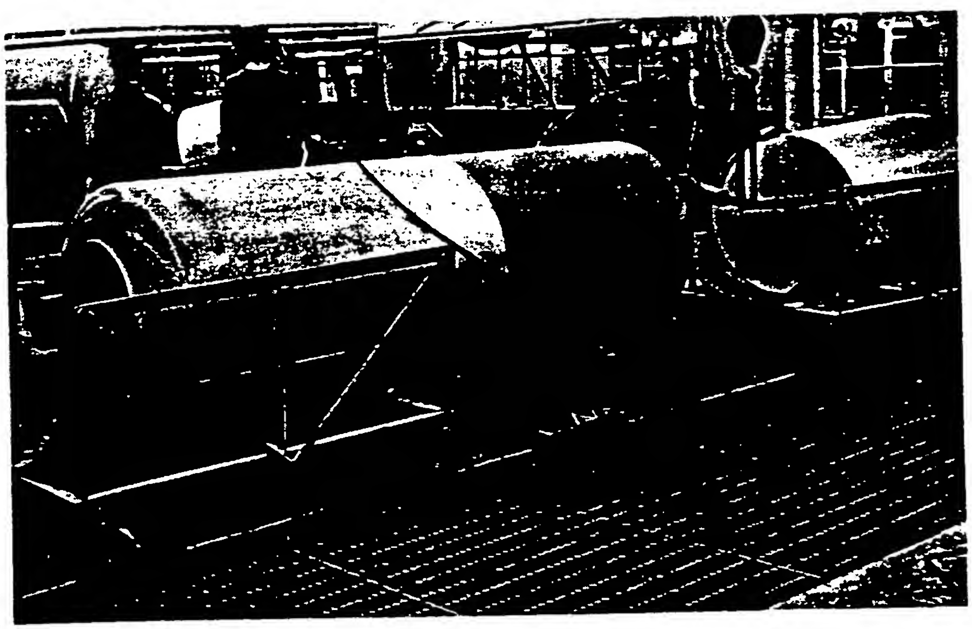


Figure 2.8 Extraction from steel mandrel of filament-wound radomes; two radomes are fabricated during single wrapping operation. (Courtesy of Lamtex Industries, Inc.)

The 1962 statistics reported that 58 million pounds of reinforced plastics went into the transportation field, 59 million into building construction, 31 million into missiles and aircraft, and 12 million into pipes and tanks. It is estimated that within principally the missile, aircraft, pipe, and tank fields at least 40 million pounds might be going into basically filament-wound products. Cost for these products could be $120 million, with an additional cost of $200 million to account for tooling, wrapping machines, and new designs.

Past and present performance within the reinforced plastics and overall plastics consumption indicate that by 1967 the filament-wound poundage will be at least double. However, present new trends in filament wrapping based on successful testing of railway tank cars, rocket motors, and pipe could very easily cause future consumption to increase at a much greater rate.

References

1. "Filament Winding Advances," *Modern Plastics*, p. 97 (February 1963), **40**, No. 6.
2. G. D. Brewer, *Industrial Research*, **4**, 4, p. 41 (April 1962).
3. "Filament Winding," *Modern Plastics*, p. 94 (October 1961), **39**, No. 2.
4. J. F. Reeves, SPI Annual Preprint, p. 8C (February 1962).
5. Poxyglas, Bulletin 45-110; Black, Sivalls and Bryson, Inc. (1961).
6. Filament Wound Railway Tank Car, **2**, 3, p. 10 (May/June 1963).
7. J. W. Carter (Black, Sivalls and Bryson, Inc.) to D. V. Rosato (personal correspondence, 6 June 1963).
8. I. Stern, *Industrial Research*, pp. 35–37 (November 1962).
9. Dow Smith, Inc., Petroleum Data Sheet, Bulletin 2000-1062 (1963).
10. A. L. Wester, SPI Annual Preprint, p. 15D (February 1962).
11. D. V. Rosato, *Asbestos*, 1st Ed., Reinhold Publishing Corp., New York (1959).
12. K. W. Pepper and F. T. Barwell, *J. Soc. Chem. Ind.*, **63**, 321 (1944).
13. R. T. Crouch, SPI Annual Preprint, pp. 15C–1 (February 1962)
14. A. M. Shibley, H. L. Peritt, and M. Eig, Army PLASTEC Report No. 10 (May 1962).
15. L. E. Gatzek and C. R. Feller, SPI Annual Preprint, p. 7B (February 1962).
16. J. J. Sewell and J. K. Kuno, SPI Annual Preprint, p. 7A (February 1962).
17. A. J. Dervy, SPI Annual Preprint, p. 7D (February 1962).
18. Ranger Capsule Details, *Astronautics*, p. 64 (January 1962) **7**, No. 1.
19. R. J. Runck and B. W. King, Battelle Memorial Institute, OTS-PB-171629 (6 June 1961).
20. F. G. McGuire, *Missiles and Rockets*, **7**, 18 (28 December 1959).
21. Lamtex Contract, *Missiles and Rockets*, **9**, 47 (4 December 1961).
22. J. F. Judge, *Missiles and Rockets*, **10**, 22 (15 January 1962).
23. United Technology Corp. (Titan III), *Missiles and Rockets*, **10**, 9 (9 April 1962).
24. Poor Man's Scout Rocket, *Data*, **7**, 4 (January 1962).

25. R. W. Larrick, United Technology Corporation, News Release, High Energy Solid Propellant Motor (1962).
26. R. W. Larrick, United Technology Corporation, News Release, Solid Propellant Rocket (1962).
27. D. V. Rosato, *British Plastics*, **33**, 8, p. 348 (August 1960).
28. A. G. Pehrson, *SPE Journal*, p. 301 (March 1962).
29. Materials and Structures, *Astronautics*, p. 74 (January 1962), **7**, No. 1.
30. Polaris A3 Fiber Glass Case, *Missiles and Rockets*, **10**, 36 (29 January 1962).
31. J. P. Kushnerick, *Aircraft and Missiles* (February 1960).
32. J. A. Kies and H. Bernstein, SPI Annual Preprint, p. 6B (February 1962).
33. J. Abel, Nondestructive Testing of Glass Epoxy Polaris Motor Cases, 18th Polaris-Minuteman-Pershing ASTM Meeting, Salt Lake City (2–3 August 1961).
34. Projects, *Aerospace Management*, **4**, 9 (December 1961).
35. Minuteman, *Missiles and Rockets*, **8**, 36 (17 October 1960).
36. Citanis, SPI Annual Preprint, p. 6F (February 1962).
37. J. P. Kushnerick, *Aerospace Management*, p. 44 (December 1961).
38. F. Wolff and T. Siuta, Factors Affecting Wound Structures (August 1961).
39. B. M. Corley, Space/Aeronautics, p. 72 (October 1961).
40. J. E. Buhl and J. G. Pulos, SAMPE *Meeting Report*, p. 325 (March 1961).
41. B. L. Duft and N. Brink, "Plastic Pressure Hull," *Undersea Technology*, (July/August 1961).
42. B. L. Duft and N. Brink, Narmco Research and Development Report (1962).
43. F. R. Barnet and C. L. Lloyd, SPE *Annual Report*, p. 357 (1958).
44. T. B. Owen and G. Sorken, AIME Annual Meeting, New York, Metallurgical Materials Association with Deep Diving Submarines (14 February 1960).
45. R. W. Rosati, News Release, Olin-Mathieson Chemical Corporation (March 1962).
46. M. Eig and H. Peritt, Army Picatinny Report 3027 (March 1963).
47. A. G. Pehrson, SPI Annual Preprint, p. 2B (February 1962).
48. R. Abelin and E. A. Wohlberg, SPI Annual Preprint, p. 2A (February 1962).
49. R. N. Dallas, SAMPE Meeting Report, p. 225 (March 1961).

3 Reinforcements

GLASSES

The high strength-to-weight ratio in filament-wound structures can be attributed largely to the reinforcement. The matrix material (or resin), though not in itself providing strength capability, can be a very important factor in limiting performance of the composite. The matrix material is essential, for it serves to bond the reinforcements together and transmits the loads to the fibers so that optimum fiber stresses can be developed before failure. Efficient strength-weight structures can exist only if the fibers of the composite have an efficient strength-weight relationship in the monofilament form. Glass fibers provide the most efficient filament structure. Oriented asbestos or organic fibers would be rated second.

Organic fibers are basically inferior to glass in this type of application because they have a low elastic modulus. Asbestos fibers have not been extensively evaluated specifically for filament-wound structures. Their initial application uses asbestos fibers as an outer jacket or coating on continuous glass filaments in order to improve certain inherent characteristics of the wound structure.

Glass Fibers

Glass fiber is one of the strongest materials now available in large quantities. It is also comparatively low in density, inexpensive, stiff,

chemically resistant, relatively submissive to textile manufacturing techniques, and capable of extensive modification in composition. The glass reinforcements applicable to winding operations are principally continuous-fiber filament, roving, yarn, and unidirectional woven tape. These forms are applied by the resin preimpregnated method or the wet method. In Figure 3.1 the forecast of growth potential for typical rocket motor cases shows glass filament as the most efficient (1) as compared to other reinforcements.

The compositions most generally used for commercial fibers are identified as low-alkali, lime-alumina borosilicates, or soda-lima borosilicates. The glass fibers most commonly used and identified as Type E are the low-alkali formulation. Type E is also known as electrical glass because of its good dielectric properties.

Type E glass is predominantly used in filament-wound vessels, because it is most resistant to attack from the atmosphere and because of its chemical durability, its ease of drawing, and its chemical availability as continuous-filament fiber (2). These factors contribute to consistency in properties as compared to other types of glass. The

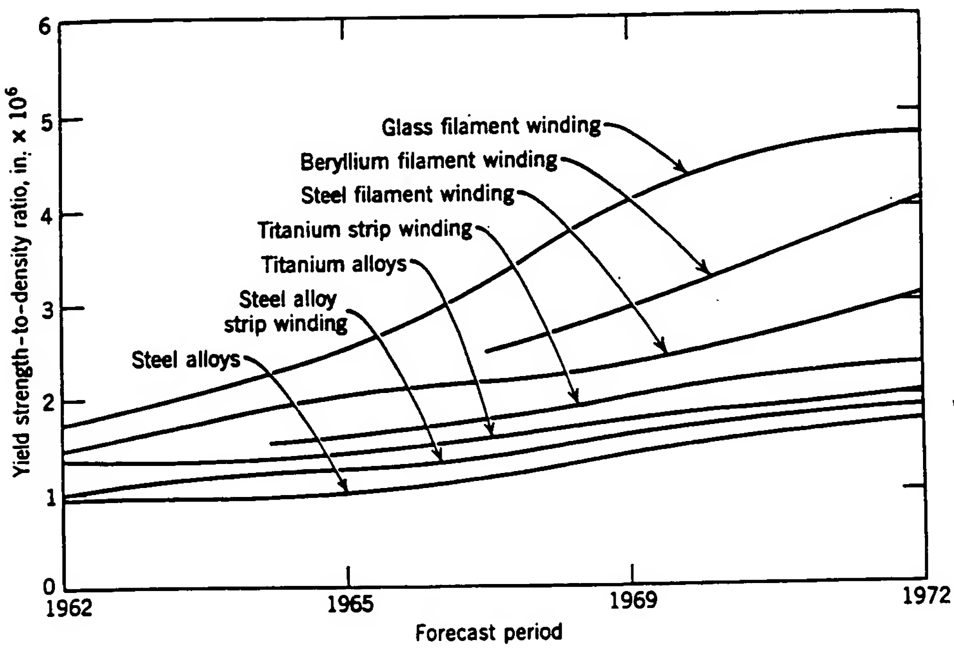


Figure 3.1 Forecast of structural performance growth potential for typical rocket motor cases. Note: Abstracted from "Aerospace Technical Forecast-1962–1972," Aerospace Industries Association of America.

Table 3.1 *Typical Fib r Glass F rmulas,[a] per c nt by weight (3)*

Type	SiO_2	Al_2O_3	CaO	MgO	B_2O_3	Na_2O	K_2O
Low-alkali, lime-alumina borosilicate (E glass)	54.5	14.5	22.0	—	8.5	0.5	—
Soda-lime borosilicate	65.0	4.0	14.0	3.0	5.5	8.0	0.5
Soda-lime borosilicate	59.0	4.5	16.0	5.5	3.5	11.0	0.5
Soda-lime	73.0	2.0	5.5	3.5	—	16.0	—
Lime-free soda borosilicate [b]	59.5	5.0	—	—	7.0	14.5	—
High-lead silicate [c]	34.0	3.0	—	—	—	0.5	3.5

[a] Fiber producers include Gustin-Bacon Manufacturing Company, Ferro Corporation, Johns-Manville Corporation, Owens-Corning Fiberglas Corporation, and Pittsburgh Plate Glass Company (4).

[b] Plus 4 per cent ZrO_2, 8 per cent TiO_2, and 2 per cent Fe.

[c] Plus 59 per cent PbO.

ease of drawing contributes to low cost. Typical fiber glass formulations are given in Table 3.1, and typical glass-laminate properties are in Table 3.2. The conventional glass-fiber diameter is 0.00038 inch. In order to increase compressive strength in reinforced laminates, its fiber diameters have increased to 0.005 in. With the larger fibers, composite epoxy-resin laminates can achieve ultimate compressive strengths up to 300,000 psi. These laminates contain 30 per cent, by weight, of resin rather than the usual 11 to 15 per cent found in the conventional glass.

Table 3.2 *Average Properties of Glass Reinforcements*

Material	Ultimate Tensile Strength, psi	Density, pounds/cubic inch	Strength/Density, 10^6 inch
Glass Filament			
Type E	250,000	0.082	2.72
Type HTS	280,000	0.082	3.04
Glass/Resin (70/30 by volume)			
Type E	175,000	0.077	2.27
Type HTS	195,000	0.077	2.54

Glass Manufacturing

The general process used for manufacturing glass textiles is that of melting glass through a platinum bushing. Glass marbles approximately ¾ inch in diameter are prepared for the bushing. However, various forms of chipped glass are sometimes used in place of the glass marbles. The bushings hold approximately 5 pounds of molten glass. The electrical heat applied to the bushing is approximately 2400°F. This temperature is controlled very closely in order to obtain the proper viscosity of the liquid glass.

Fiber glass reinforcements are supplied in several basic forms. These forms allow for flexibility in cost, strength, and choice of process. Many variations of the basic forms have been developed over the years to meet performance and economic needs, which vary over a wide range.

Glasses are prepared by melting together oxides and oxide-producing materials. The melt is then cooled rapidly enough to prevent devitrification. Most fibers are produced by the mechanical drawing process. Other commercial processes involve steam or air blowing and flame blowing. These latter processes produce wool and staple or short fibers. Only the mechanical drawing process produces continuous fibers which are specifically used in filament-winding operations.

From small orifices in the bushing, continuous glass filaments are drawn. It is estimated that a filament is pulled at a speed of 2 miles per minute in order to form a continuous filament having a controlled diameter. The commercial practice is to draw a large number of filaments in one operation, for example, groupings of 51, 102, or 204 continuous filaments. The most common practice is to pull 204 filaments, which in turn form a strand. This strand is then gathered around a winding tube.

Yarn and Roving. Continuous glass strand is ordinarily supplied in the form of yarn and roving. Continuous glass filaments, usually amounting to the 204 individual filaments, make up the glass strand immediately after the mechanical drawing operation. Production of glass roving only requires plying together the desired number of (untwisted) glass strands. If twisted yarns are to be produced, the 204-filament strand is put through a twist machine.

In turn twisted yarns can be plied together in order to meet any configuration desired. Untwisted multi-strands are also made avail-

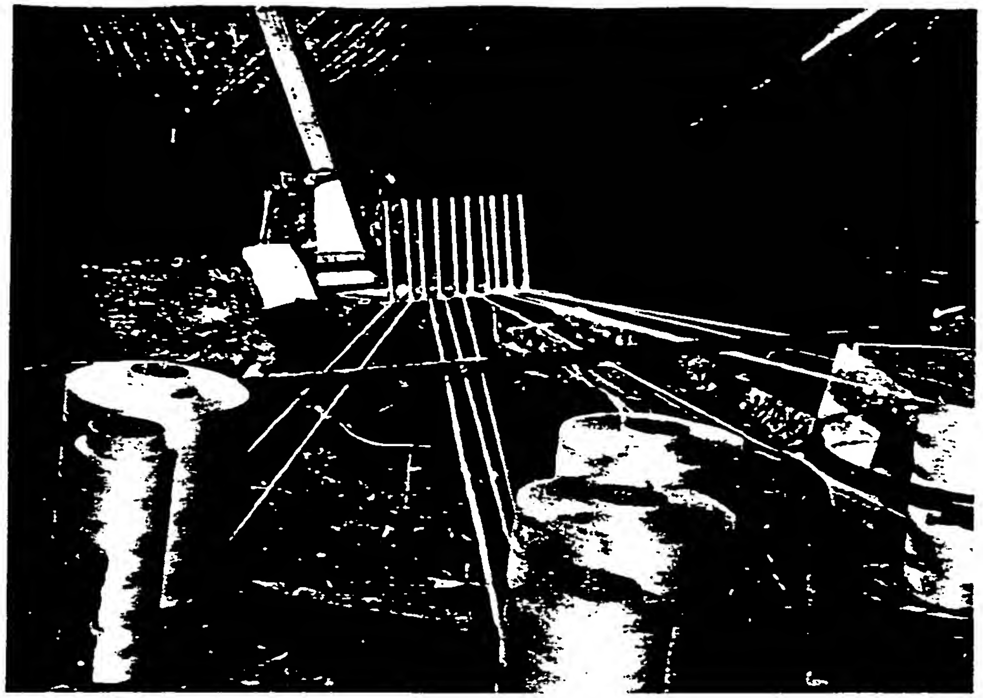


Figure 3.2 Railway car tank tape/band winding operation; separate glass roving spools on a reciprocating carriage are fed through epoxy resin and formed into a flat tape. (Courtesy of Black, Sivalls and Bryson, Inc.)

able in the form of "spun roving." A continuous single strand is looped many times upon itself and holds the roving together with a slight twist.

While the terms "rovings" and "yarn" are sometimes used interchangeably, they definitely have different meanings. These yarns and rovings are used to fabricate the majority of filament-wound vessels. The nomenclature of glass fiber yarns differs from that used for other types of textile fibers, because there are many different glass fiber varieties of nearly identical characteristics.

A typical glass yarn is identified as ECG-150-3/2. Interpreted, this designates an electrical type glass (E), a continuous glass filament (C), a fiber diameter of .00038 inch (G), an average of 15,000 yards per pound of basic strand (150), and 6 strands in finished, plied yarn (3/2).

The initial three letters are used to identify the basic glass strand used in producing the yarn. The first letter defines the glass composition (E) for electrical and (C) for chemical. The second letter indicates the type of fiber (C) for continuous filament and (S) for

staple fibers. The third letter defines the average fiber or filament diameter from which the yarn is made.

Letter Designation	Fiber Diameters
A	Over .00006 inch–.00010 inch
B	.00010 inch–.00015 inch
C	.00015 inch–.00020 inch
D	.00020 inch–.00025 inch
E	.00025 inch–.00030 inch
F	.00030 inch–.00035 inch
G	.00035 inch–.00040 inch
H	.00040 inch–.00045 inch
J	.00045 inch–.00050 inch
K	.00050 inch–.00055 inch
L	.00055 inch–.00060 inch

The number following the letters is called the "count of individual strands." This number represents the hundreds per pound of the strand. For example, the number 150 represents a strand of 15,000 yards per pound.

The final set of numbers (as in example 3/2) designates the yarn construction and consists of two numbers separated by a diagonal line. The first represents the number of strands twisted together to form unbalanced yarn. The second, after the virgule, represents the number of plies of this unbalanced yarn needed to make a plied yarn. The designation 3/2 is used for yarn consisting of three strands twisted together to form a yarn, two of which are then combined to form a plied yarn. The principal reason for the twist in yarn is to prevent filaments from separating when tension is relaxed. A typical twist is one torsional turn per linear inch of material.

Glass fiber rovings are made by gathering a number of continuous-filament strands and winding them to form cylindrical packages. Each strand, which is called an "end," consists of many fine monofilaments. Rovings provide the lowest-cost reinforcement for filament winding.

Continuous filament strand roving is available in a variety of ends. The most common are 20 and 60 end counts.

General Properties. Chemical durability becomes especially important when glass is produced in the form of fibers. Glass, even in massive form, is not immune to various kinds of chemical attack. In fibrous form, because of vastly greater surface area, attack is greatly

accelerated. A glass marble ¾ inch in diameter, for example, has a surface area of 1.767 square inches (5). This amount of glass can be drawn into a fiber 0.0002 inch in diameter and 100 miles long, with a resultant surface area of 4,000 square inches.

Commercial glass fibers generally range from 0.00023 to 0.00038 inch in diameter. Tensile strengths of at least 500,000 to 600,000 psi can be obtained from the virgin commercial fibers. Various factors affect the strength of these fibers, so that reduced properties are obtained immediately after the fibers are drawn from the pushing. The most important factor is related to surface condition. The conventional humid atmosphere in the immediate areas where filaments are drawn will produce at least a 20 per cent drop in tensile strength. In actual practice, by the time the glass is wrapped around a winding tube, its strength may be down as low as 250,000 psi.

Previous work associated with the determination of the tensile properties of continuous glass filaments has been primarily with glass monofilaments. The tensile strength of dry, continuous glass filaments is generally reported as being lower than 250,000 psi. However, fiber stresses higher than 300,000 psi have been noted from rupture tests of unidirectional, glass filament–resin composites made of these glass strands. This fact indicates that the methods of evaluating dry glass filaments in the form of strands or rovings are not of qualitative value and do not correlate with the mechanical properties which are observed in composites. The various investigators have been conducting studies to initiate new techniques for testing glass strands which would correlate with the strength levels observed in composite structures (6).

Tensile testing of dry strands of glass filaments results in uneven loading of glass filaments, and therefore lower strengths are obtained. By resin-impregnating the filaments and locking-in of a pretensioning load during cure of the impregnant, a more uniform failure in testing the glass occurs. When epoxy resins are used, extremely high tensile-strength values can be obtained. The test becomes very sensitive to the amount and the manner of applying the resin. With a low-strength, high-elongation vinyl impregnant, this objectionable feature of the test was eliminated. The results of tests with the vinyl system produces a 98 per cent confidence level.

Packaging. It is apparent that the materials used and the winding process constitute the most important steps in the fabrication of efficient wound vessels. However, packaging of the fibers is another important aspect. Regardless of reinforcement strengths, improved

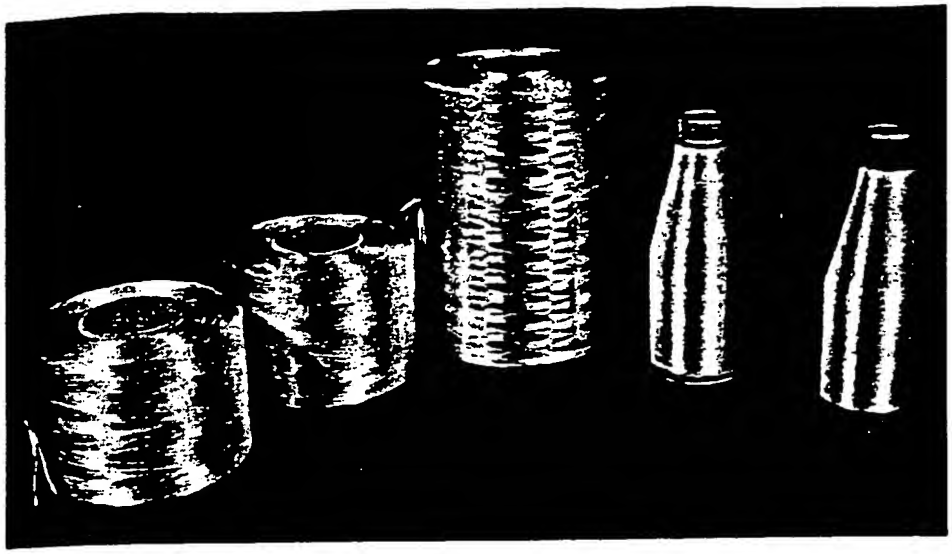


Figure 3.3 Typical glass filament reinforcement packages. Left to right: 12-end roving, 7-pound roll; 20-end roving, 7-pound roll; 12-end roving, 15-pound roll; 150 1/0 E yarn; and 150 1/0 HTS yarn. (Courtesy of Owens Corning Fiberglas Corp.)

surface treatments of reinforcements, improved matrix materials employed, and controlled fabrication processes, the ultimate capabilities of the vessel are also directly related to the manner in which glass fibers are packaged. A package should be constructed to reduce the possibilities of twist to a minimum. Twisting of the glass during winding causes abrasion of the filaments and unequal fiber tension and results in a lowering of the composite strength.

New techniques for packaging are being developed by the various glass fiber producers. Present procedures involve pulling yarn from the outside of a package. In case of rovings, they are pulled from the inside of the package.

Sizing or Coupling Agents

Glass fibers tend to abraid from the time they are drawn from a bushing and wrapped around a winding tube. To prevent the fibers from abraiding each other, a "size" is applied to the individual fibers just before they are formed into a strand. Size refers to any coating applied to textile fibers in the operation of forming. They may contain one or more functional components, that is, lubricant alone, lubricants and binders, binders, and coupling agents (7). Mineral oil

lubricants are used predominantly to reduce fiber abrasion. Binders are also extensively used in order to bond or hold the filaments together. The most commonly used binder is dexterized starch with small amounts of bonding agents such as gelatin or polyvinyl acetate added.

Coupling agents are employed to improve the bond between the glass and the resin binders. These agents are also identified as "finishes" in the United States and "keying agents" in England. The type of coupling agent employed depends both upon the composition of the glass and the resin. At least two general types are employed commercially. One is represented by a chrome complex and the other by silane compounds.

The ideal coupling agent is a molecule containing two kinds of groups, one of which reacts to adhere firmly to the glass while the other combines with the resin (8). For polyesters, the glass-coupler has been chromium ion or silane, while the resin-coupling end has been a monomer such as methacrylate, allyl, or vinyl, capable of copolymerizing with the polyester-monomer blend. Some of the more popular finishes for polyesters are:

No. 114: methacrylatochromic chloride.

Volan A: No. 114, hydrolyzed to remove the chlorine and provide free hydroxyl.

NOL-24: allyltrichlorosilane-resorcinol condensate.

B.J.Y.: chloroallyloxyvinyldichlorosilane.

Epoxy resins make use of these finishes, especially the "Volan," as well as others specifically designed for reaction with epoxide, for example, "Linde" A-1100 (amino triethoxysilane), etc. However, the trend is toward the use of epoxy resins directly on the glass. They must be applied shortly after the spinning of the filament or the heat-cleaning of the cloth, in order to exclude moisture. Once the glass fibers are stabilized by coating with epoxy, there is no urgency about completing the fabrication of the reinforced part. The epoxy is then a binder as well as a coupling agent. Not only epoxy resins but polyesters as well may be employed for the subsequent impregnation. The epoxy-polyester hybrid combines the low cost of the polyesters with the superior stamina of the epoxies.

Some investigations of the use of commercial yarn, roving, or fabric for rocket-motor cases indicate that better results are obtained by first heat cleaning in oxygen-enriched air at temperatures of 1175°F for 8 to 12 seconds. The cleaned glass is then coated with a bonding agent. Best results were obtained when the latter was applied as a vapor.

The treatment in oxygen-enriched air produces a surface to which A-1100 bonds particularly well (9).

Glass fiber rovings or yarn coated with plastic-compatible sizing is now available for the reinforcement of filament-wound vessels. The rovings can be used directly without further processing. Since there is definitely room for further improvement and development of sizing and coupling agents to increase the reinforcement strengths, investigations continue. The development of new high-modulus glasses brings with it the problem of finding suitable and perhaps new coupling agents for the various compositions developed.

In all probability, a major breakthrough in improving the properties of glass fibers will occur when a suitable size is applied on freshly drawn fibers in order to protect them from abrasion and atmospheric attack (10).

High-Modulus Glass Fiber

Research has been conducted in order to increase the glass fiber modulus. Most of the filament-wound developments have been directly concerned with rocket motor bodies. Commercially available glass filament in yarn or roving form (such as E-glass filaments) have definitely advanced the state-of-the-art in developing more efficient structures. In order to further advance the state-of-the-art, a higher modulus of elasticity is desired. The higher modulus glass can increase buckling resistance and provide a better match of the glass filament-wound material to metallic inserts (11).

Conventional E-glass fibers alone have a modulus of 10.5 to 12×10^6 psi. When used in a wound structure with conventional epoxy resin, modulus values can be achieved up to 9×10^6 psi. High-modulus glass containing a small amount of beryllium oxide can produce moduli properties up to approximately 17×10^6 psi (Owens-Corning YM31A fiber alone) (12). Continuous fibers can be drawn utilizing this glass composition which has a strength equivalent to that of E-glass. Recent developments have been made in which the high-modulus glass can be twisted and plied into yarns. Table 3.3 compares properties of YM31A with E-glass.

The high modulus has been obtained through the combined efforts of government agencies and industrial organizations. Initial data indicate that the fatigue properties of this high-modulus glass are approximately equivalent to E-glass (13). The stress-rupture characteristics of these glasses are superior to those of E-glass. The strength properties can be equal or superior to E-glass but are dependent on

Tabl 3.3 Single-Fiber Strengths and Modulus of E-Glass and YM31A

Fiber	Temper-ature, °F	Tensil Strength, $\times 10^3$ psi	Modulus f Elasticity, $\times 10^6$ psi
E	75	500	12.4
	400	470	12.2
	750	350	12.1
	950	280	12.0
	1200	150	—
YM31A	75	500	16.8
	400	460	16.5
	750	320	16.0
	950	210	15.5

the use of an optimum resin-finish combination. Equivalent thermal characteristics have been obtained regarding specific heat, thermal expansion, and thermal conductivity.

Other government-sponsored industrial research and development programs to increase glass modulus have been successful. In addition to the program with Owens-Corning Fiberglas, Inc., resulting in glass fiber YM31A, other (14) programs have resulted in H. M. 905, produced by Imperial Glass, Inc., Bellaire, Ohio; and No. 29A, produced by Houze Glass Corp., Point Marion, Pennsylvania. In Table 3.4 a

Table 3.4 Tensile Strength on Single Glass Fibers

Nominal Fiber Diameter, inch	Breaking Force, pounds	Tensile Strength, psi
0.001	0.084	88,100
0.002	0.266	73,133
0.003	0.474	58,000
0.008	1.55	30,800
0.009	1.77	28,800

American Optical Company round clad fibers, 10-inch length (15).

comparison is made of tensile strength versus fiber diameter of a special American Optical Co. glass.

High-Temperature Glass Fib rs

Research is in process on producing high-temperature glass fibers which will extend the capability of available reinforcements to temperatures of 2000°F and higher (16). Glass filaments have been developed with tensile-strength properties in excess of 100,000 psi at 2000°F. Room temperature strengths for these fibers are reported to be in excess of E-glass (17).

Virgin E-glass fiber has a tensile strength of 500,000 psi at room temperature. The tensile strength gradually reduces until it yields at approximately 800°F (18). Approximately 50 per cent deterioration in strength occurs when these virgin fibers are coated with a sizing or finish. To date manufacturing processes have required techniques of applying finishes which deteriorate the virgin fiber. The finishes are necessary in order that the fibers can be handled and that proper bond can be developed between the glass and resin.

Different basic developments are being conducted using vitreous silica materials in order to develop elevated temperature resistance and to increase modulus of elasticity (19). Tensile tests conducted on laboratory filaments have developed relatively high-temperature-resistant and high-modulus fibers with basic room temperature properties of up to 500,000 psi tensile strength and 20×10^6 psi modulus (20).

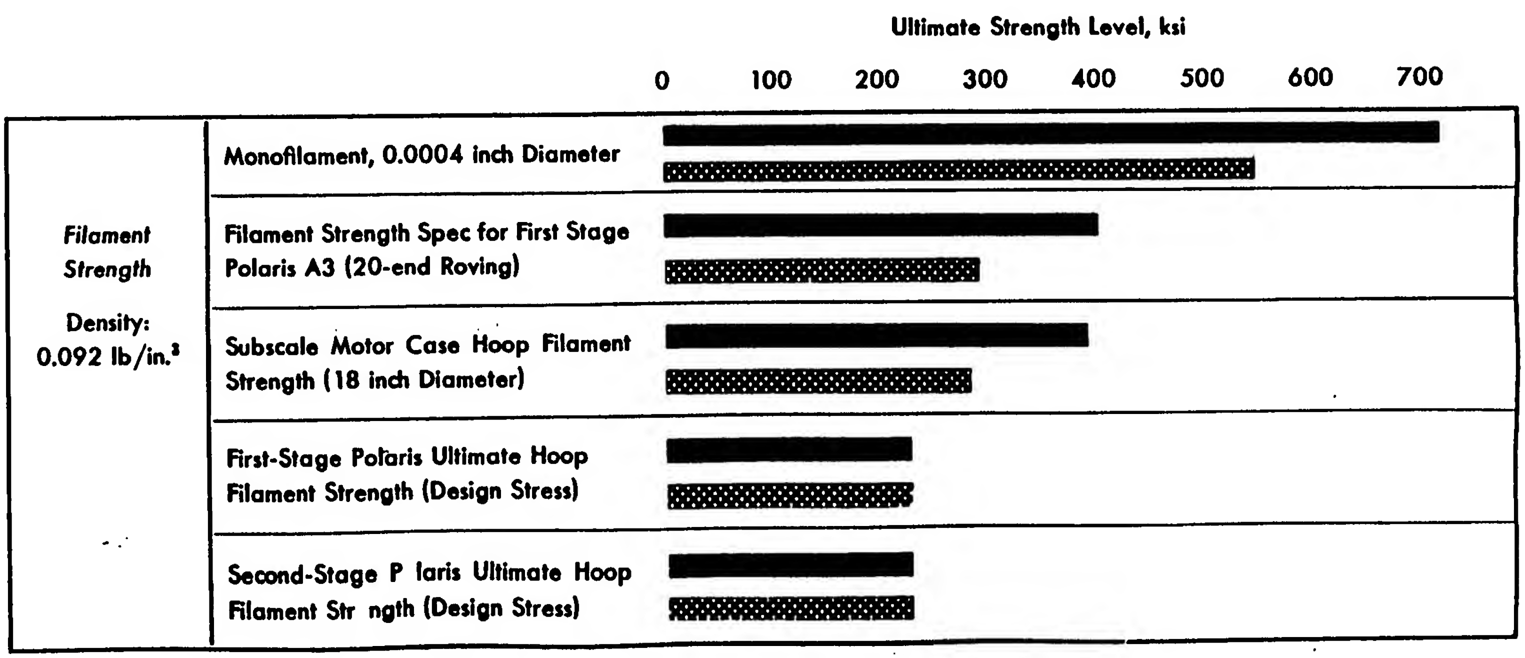
An alumina-silicate composition based on kaolin has produced fibers tested as high as 19×10^6 psi modulus at 1500°F. New techniques for drawing these fibers are being developed. One promising approach is the use of a glass rod made of the high-melting composition. The glass rod can be heated inside a tubular graphite susceptor in an inductor coil. At a specified temperature, the fiber can be drawn.

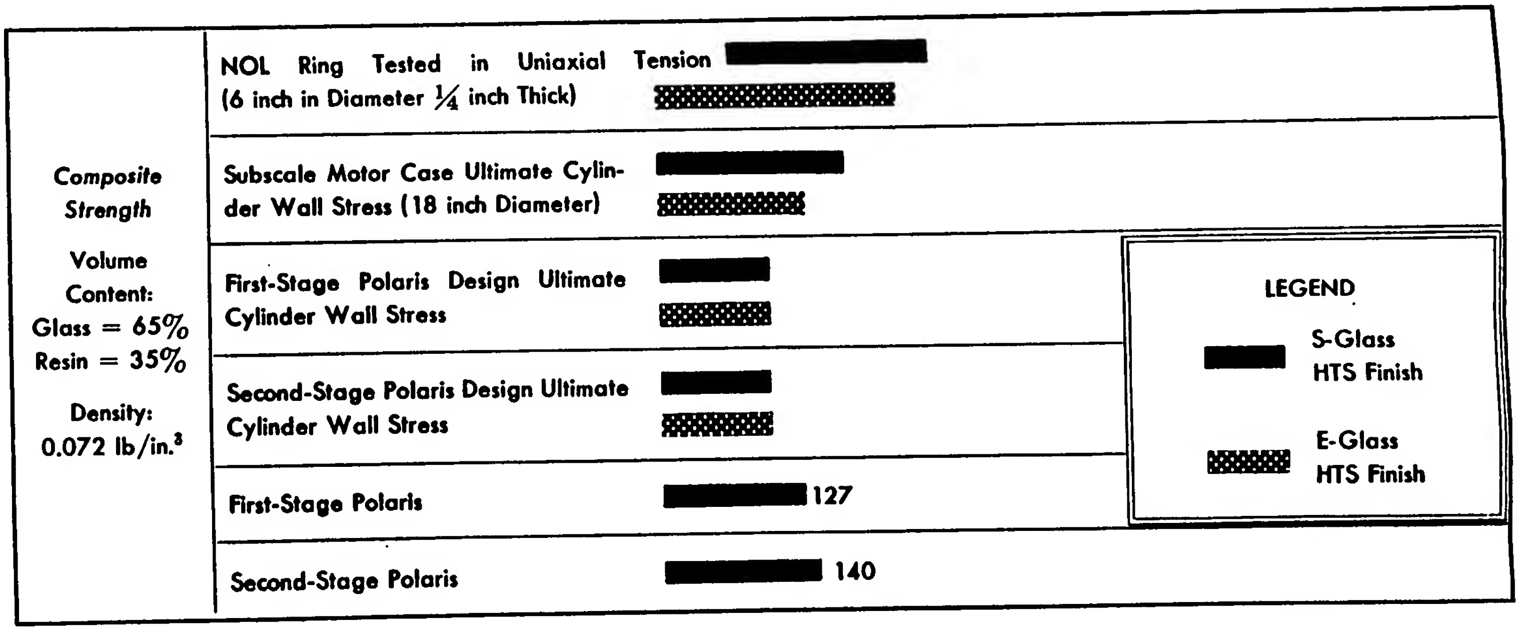
High-Tensile-Strength (HTS) Treatment

Conventional E-glass fibers treated with a special Owens Corning finish have been studied to find out how they can be made to retain more of their virgin strength. As previously reported, virgin strength values of up to 600,000 psi exist. However, usable values of 250,000 psi are achieved (21).

New processing techniques have been developed which have increased the design allowables of glass fibers by approximately 10 per

Table 3.5 *Ultimate Strengths of Types S- and E-Glass Filaments (1)* (Courtesy of Lockheed Missiles and Space Company)




Composite Strength
Volume Content:
Glass = 65%
Resin = 35%
Density:
0.072 lb/in.³
NOL Ring Tested in Uniaxial Tension (6 inch in Diameter ¼ inch Thick)
Subscale Motor Case Ultimate Cylinder Wall Stress (18 inch Diameter)
First-Stage Polaris Design Ultimate Cylinder Wall Stress
Second-Stage Polaris Design Ultimate Cylinder Wall Stress
First-Stage Polaris
127
Second-Stage Polaris
140
LEGEND
S-Glass HTS Finish
E-Glass HTS Finish

cent. This treatment is designated HTS (High Tensile Strength) and has been used on both E- and S-glass. A comparison of E-glass with 801 finish and E-glass with HTS finish shows an increase from 350,000 to 390,000 in NOL fiber stress tests. This coating treatment, while not increasing the inherent strength of the glass filaments, is effective in retaining a higher percentage of the inherent strength of the filaments by its protective effect against abrasion and chemical attack (22, 23).

New High-Strength Fibers—"S" Glass

The Owens-Corning Fiberglas Corporation, under a development program sponsored by the Air Force, developed a new glass fiber reinforcement which has structural properties in order of magnitude greater than the previously standard E-glass. Originally designated AF-994, this new glass fiber is now marketed as "S"-glass.

The composition of this glass fiber has been reported as

SiO_2—64 per cent
Al_2O_3—26 per cent
MgO—10 per cent

and its fiber diameter as 38×10^{-5} inch. Virgin single fiber strength of S fibers is approximately 700,000 psi as compared to 500,000 psi fiber stress for E-glass (Table 3.5). This significant increase in fiber strength has put the strength of the glass-epoxy filament-wound composites higher than structural metals on a volume basis. Before

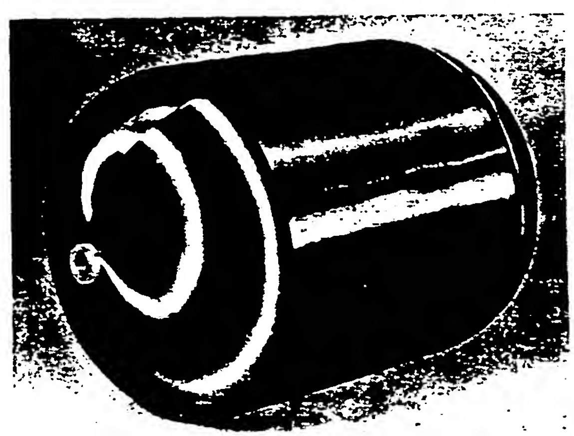


Figure 3.4 Cylindrical pressure vessel fabricated using high-strength steel wire and epoxy resin. (Courtesy of Aerojet-General Corp.)

the development of these fibers, glass-filament-wound plastics were not stronger than metals on a volume basis but on a specific or weight basis. The strength-to-weight ratio of "S"-fiber composites is further enhanced by the slightly lower density of .090 pounds/inch^3 as compared to a density of .092 pounds/cubic inch for E-glass.

Another improvement over E-glass fibers offered by S-glass is the higher strengths retained at elevated temperatures. At 1400°F, E-glass yields and loses its fiber strength, whereas "S" still retains a strength of 180,000 psi and does not yield until a temperature of 1600°F is reached. A comparison of "E" filaments and "S" filaments is shown in Figure 3.4.

It is anticipated that "S"-glass fibers will dominate future applications for filament-wound composite systems, both because of the improved structural strength and because of the greater strength retention at elevated temperatures. A comparison of various glass fibers with "S"-glass is shown in Table 3.6.

Leached Glass

Another form of glass fiber is identified as leached glass. This type of product can be considered E-glass which has been subjected to an acid bath. However, it is not used in filament-wound structures, for it retains very little of its E-glass tensile strength (24). It is used principally to provide a reinforcement for ablating plastics used in re-entry nose cones or heat shields of missiles.

Leached E-glass followed by annealing produces almost pure silica fibers. These fibers are readily affected by moisture and handling. It is known that silica glass does not have a high modulus and that the addition of silica tends to lower the modulus. However, at 2200°F, the modulus increases from 12 to 15 per cent over the room temperature value. It is also noteworthy that the tensile strength is retained up to 2200°F.

Work with nonvitreous fibers in filament winding is a relatively new area of effort. It can now be considered as a laboratory curiosity, the task being to produce new fibers for the future.

Uses of Fibrous Glass

Fibrous glass, also known as glass fiber and fiber glass, has thousands of uses in all its forms. However, it is used mostly for thermal and acoustical insulation. The short fibers, known as wool or insulation fiber, are manufactured in such forms as batts, rolls, blankets, board,

Table 3.6 Average Properties of Individual Glass Fibers

Physical Properties	Electrical, "E"	Intermediate Temperature, X37B	High Temperature, "S"-Glass	High Modulus, YM31A	Low Dielectric Constant, 556	Lead Glass, 498	Chemical, "C"
Tensile Strength (psi)							
at 80°F	500,000	600,000	650,000	500,000	300–350,000	—	450,000
at 500°F	430,000	550,000	610,000	420,000	—	—	—
at 1000°F	250,000	320,000	353,000	175,000	—	—	—
Modulus of Elasticity, $\times 10^6$ psi							
at 80°F	10.5	12.25	12.33	15.9	7.5–7.7	8.0	—
Density (Grams/cm^3) at 80°F	2.55	2.55	2.49	2.89	2.15	4.2–4.3	2.49
Coefficient of Thermal Expansion —Linear (°F)	2.8×10^{-6}	—	—	—	—	—	4.0×10^{-6}
Coefficient of Thermal Conductivity— $\frac{\text{Btu–in.}}{\text{hours–square feet–°F}}$	6–6.4	—	—	—	—	—	7–7.3
Specific Heat (Bulk Glass)							
at 80°F	0.185	—	—	—	—	—	0.188
at 500°F	0.244	—	—	—	—	—	0.252
at 1000°F	0.275	—	—	—	—	—	0.290
Index of Refraction at 80°F	1.547	1.548	1.523	1.635	1.47	1.69	1.54
Dielectric Constant							
at 10^4 Cycles	6.4–6.5	—	—	—	—	9.78	7.2–7.5
at 10^{10} Cycles	6.1–6.4	—	5.6	—	4–4.2	—	6.8–6.9
Dissipation Factor							
at 10^4 Cycles	0.001–0.002	—	—	—	—	—	0.008–0.009
at 10^{10} Cycles	0.005–0.006	—	—	—	0.001	—	0.010–0.013
Volume Resistivity (Ohms/cc)							
at 72°F	$2 - 5 \times 10^{12}$	—	—	—	—	—	—
at 1320°F	10^7	—	—	—	—	—	—
at 1600°F	10^5	—	—	—	—	—	—
at 2300°F	10^2	—	—	—	—	—	—

and mat (25). They are used in scores of ways throughout the economy, for example, in buildings, appliances, automobiles, and other transportation equipment.

The long fibers, known as continuous filaments, are produced in smaller amounts, but demand is increasing because of new uses and improved products such as filament-wound vessels. They are used mainly for reinforcing plastics and for making yarn to be woven into textile materials. Filament-wound vessels, plastic furniture, lamp shades, boats, auto bodies, and fishing rods are only a few of the products strengthened by glass fiber reinforcement. Glass yarn is woven into curtains, drapery fabrics, protective clothing, and electrical insulation tape.

World Fibrous-Glass Market

The United States fibrous-glass industry has developed rapidly since it began commercial production about 25 years ago, and the U.S. is now the world's largest producer. Nine companies annually produce more than 800 million pounds of fibrous glass, valued at nearly a quarter of a billion dollars (25).

Estimated West German production in 1960 was 80 million pounds; the United Kingdom produced 60 million pounds; and France and Italy produced 45 million pounds each. However, small-scale production is common throughout the world. Plants are located in many European and North and South American countries, in at least one African country, and in Israel, Japan, Australia, and New Zealand. The extent of production behind the Iron Curtain is unknown, but it is considered to be large.

The annual value of U.S. foreign trade in fibrous glass cannot be determined exactly, but the total, including both sales and investment returns, amounts to several million dollars. The only fibrous glass products classified separately in U.S. export statistics are textile glass fibers and glass staple and tow, which in 1960 amounted to 414,919 pounds valued at $346,044. However, the import statistics of foreign countries furnish additional information. Canada imported from the United States glass balls, rods, and marbles valued at $487,527 and glass fiber valued at $1,203,204. Germany, Belgium and the Netherlands, and Italy each imported a half million dollars or more of U.S. fibrous-glass products.

United States producers have rather extensive interests in foreign firms, either through part ownership or licensing agreements. High import duties, protecting domestic producers, have induced U.S. in-

vestments in some countries. The formation of the European Common Market and the European Free Trade Association will result in higher import duties in European countries.

The use of fibrous glass is expanding throughout the world, and new products are being developed. At the same time, competition is increasing. Nevertheless, if the U.S. industry aggressively pursues foreign markets, there seems little question that it will maintain an important role in the world market.

Boron Fibers

The boron filament (26) has resulted from a program whose initial objective was to survey the field of elements and compounds and choose candidate materials which would have the necessary physical properties to be an effective reinforcement, provided they could be made into a filament form. This program used the criteria of high melting point and low density as the basis for the selection of candidate materials.

Boron was chosen as the prime candidate material for study because, in addition to having outstanding physical characteristics relative to the initial criteria, it had previously been prepared in a pure form by a vapor deposition technique and had exhibited desirable bulk properties. The vapor deposition technique was considered to be amenable to the formation of continuous lengths of filament, and has proved to be excellent in this regard based on tests conducted at Texaco Experiment, Inc.

Boron filament properties have compared favorably with "E"-glass with respect to usable strengths, and the modulus of elasticity of the boron filament is approximately five times that of "E"-glass even though the densities of the two materials are about equal. Composites have been fabricated and have exhibited a high percentage conversion of the filament properties to those of the composite.

Boron was chosen as the material to be investigated further as a result of the materials survey. It possesses an attractive density, 0.085 lb/inch^3 (15 per cent lighter than aluminum); is extremely hard, greater than 9 on the moh's scale; has a high melting point in certain crystallographic forms, 3700°F; and has moderate oxidation resistance. It has also been successfully deposited by several investigators using chemical vapor plating techniques to obtain a relatively high-purity product.

There are two promising methods for boron deposition. The first is the thermal decomposition of the halide or the hydride. This is

accomplished by passing the boron compound vapor over a surface maintained at a temperature greater than the decomposition temperature of the vapor. Boron is deposited on the surface, and the other decomposition products exit with the gas stream. The second method is the vapor-phase reduction of a boron halide by a gas, such as hydrogen. Again a heated surface is required, near which the two gases react, plating boron on the surface and producing hydrogen halide, which is removed with the gas stream. The latter method has received considerable effort and is used to obtain the present filaments. Various methods can be used to obtain the required temperature on the plating surface, such as radiant heating, utilization of a muffle furnace, or electrical resistance heating. Electrical resistance heating of a tungsten wire has been used primarily in this study, although successful boron depositions have been obtained on molybdenum, tungsten-rhenium alloy, aluminum, graphite, and glass, which were heated by a variety of techniques.

The filaments formed to date have exhibited strength properties which compare very favorably with those of other currently used materials on a direct comparison basis. However, the true potential of these filaments is demonstrated when these values are compared on a specific strength (the strength divided by the material density) basis, as is shown in Table 3.7. As can be seen, the boron is matched only by glass in the actual and specific tensile strength properties, both being significantly greater than other materials. In addition, the tensile modulus of elasticity column shows that the boron has greater than five times the modulus of "E"-glass and is equaled in specific

Table 3.7 Comparison of Tensile Properties of Boron with Other Materials

	Strength		Modulus	
	Ultimate, $\times 10^3$ psi	Specific, $\times 10^6$ in.	Ultimate, $\times 10^6$ psi	Specific, $\times 10^6$ in.
Boron: Bulk	350	4.1	63	740
Batch Filament	500	5.3	60	640
Continuous Filament	400	4.0	60	600
E-Glass	500	5.4	10.5	110
Beryllium Wire	90	1.3	44	660
Steel Wire	600	2.1	30	110
Titanium	240	1.5	19	120

modulus only by beryllium, whose tensile strength is considerably less.

Parallel composites made of boron fibers with epoxy resin resulted in ultimate flexural strength of 257,000 psi and modulus of elasticity of 38.3 and 10^6 psi. These special laminates, 80 per cent by volume of boron, also produced final tensile strengths from 217,000 to 344,000 psi and modulus of 16.6×10^6 psi.

Hollow Glass Filaments

A number of glass companies have, over the past few years, made hollow glass fibers in an attempt to increase section modulus and buckling resistance without increasing the absolute weight of the composite. The outside diameter of these cylinders is still on the order of .00050 inch. Testing of NOL specimens indicates that the ultimate tensile strengths, compressive strengths, and the moduli of hollow fibers are not as high as those of the solid fibers. The buckling resistance of the hollow fibers is superior to that of the solid fibers on a weight basis. The potential of hollow fibers is questionable at this stage of development, for the additional buckling resistance is coupled with a reduction in the strength of the composite.

METALS

Investigators have been evaluating the potential efficiency of filament-wound structures that use high-strength wires (27). Theoretical analysis indicated that wires can potentially produce extremely highly efficient structures based on strength-to-weight requirements. At the present time, the major emphasis is on developing and evaluating the basic wire (28).

Metal Wire

Tests have been performed on certain new commercial steel wires which indicate extreme reliability in the strength properties of the wire. The highest tensile strengths obtained were 600,000 psi with 0.003-inch diameter steel wire (29). The modulus of elasticity for this steel wire approximates what is expected in homogeneous sheets. Values ranged from 26 to 30×10^6 psi. Tables 3.8 and 3.9 provide additional information on metal wires and fibers (30), which typify the conventional type of commercially available products. The more conventional steel wires have tensile strengths of 400,000 psi (31). Steel wire is usually round, but it can also be square, hexagonal, ellipti-

Table 3.8 Properties of Fibers and Wires (30)

Fiber	Specific Gravity	Length, Inches	Diameter, μ	Tensile Strength, $\times 10^{-3}$, psi	Modulus of Elasticity, $\times 10^{-6}$, psi	Heat Resistance, °F	Coefficient of Linear Expansion
Synthetic-Inorganic							
Conventional glass (Type E)	2.6	—[a,b]	5–15	400	10.5	600[c]	2.8
						1500[d]	
Beryllium glass	2.6	—[a,b]	5–15	280	12–20	1500[d]	6
Quartz (fused silica)	2.2	—[a,b]	8–10	100–350	10–25	3500[c]	5–7
Carbon	1.8	—[a,b]	1–100	20	1–4	6200[e]	1–3
Aluminum silicate	2.7	up to 10	2–20	100–600	2–15	3300[d]	1–8
	3.9						
Graphite	1.6	up to 4	2–30	2–20	—	6764[f]	0.6–4
	2.2						
Rock Wool	2.8	up to 4	1–22			2800[d]	2–6
Natural-Inorganic							
Asbestos	2.5	up to 3	0.02	100–200	20–25	2770[d]	
Metals and Refractories							
Steel	7.8	—[a,b]	1–25	200–400	20–30	2920[e]	8–10
Aluminum	2.8	—[a,b]	4–20	60–90	10	1212[e]	17–20
Tungsten	19.3	up to 1	20	200	58	6150[e]	4.5
Tantalum	16.6	up to 0.5	5	70–90	28	5390[e]	6.6
Molybdenum	10.2	up to 0.5	5–20	—	42	4700[e]	5.4
Magnesium	1.8	—[a,b]	6–15	40	6	1200[e]	8–20
Synthetic-Organic							
Fluorocarbon	2.2	—[a,b]	20	47	0.4	525[f]	
Polyester	1.4	—[a,b]	10–25	100	—	480[e]	
Acrylic	1.2	—[a,b]	10–25	50	—	450[e]	
Polyamide	1.1	—[a,b]	10–40	70–120	—	480[e]	
Cellulose acetate	1.3	—[a,b]	11–44	25	—	500[e]	
Regenerated cellulose (rayon)	1.5	—[a,b]	10–40	30–105	—	400[d]	
Natural Organic							
Cotton	1.6	up to 2	17	50–110	—	275[g]	
Sisal	1.3	up to 24	19	120	—	212[g]	
Wool	1.3	up to 15	28	29	—	212[g]	

[a] Filament. [b] Staple. [c] Softens. [d] Decomposes. [e] Melts. [f] Sublimes. [g] Used up to this temperature.

Table 3.9 Properties of Different Alloys

Alloy	Composition	Density, pounds/inch^3	Melting Temperature, °F	Coefficient of Linear Expansion, 10^{-6}/°F	Modulus, psi, $\times 10^6$	Tensile Strength, psi, .006 wire	Strength/Weight, Inches
High-Carbon Steel	Typical % Carbon .90	.278	2800	6.5	30	575,000	2,070,000
Tungsten	99.95%	.697	6170	2.4	50	420,000	603,000
Molybdenum	99.9	.369	4760	2.7	50	300,000	814,000
Titanium	13V-11Cr-3 Al	.164	3300	4.7	17	320,000	1,950,000
Copper	99.999%	.324	1981	9.2	16	60,000	185,000
Silver	99.999%	.379	1761	10.9	11	30,000	79,100
Platinum	99.999%	.775	3224	4.9	21	57,000	73,600
Nickel	99.999%	.322	2651	7.4	30	87,000	270,000
Aluminum	High Purity	.097	1220	13.3	10	24,000	247,000
Aluminum	56 S Alloy	.095	1220	13.3	10	42,000	442,000
Rene 41	Super Alloy	.298	Not Available	6.63	32	300,000	1,005,000
Stainless Steel	302	.278	—	6.6	29	347,000	1,250,000

cal, triangular, half-oval, flat, or even tear-shaped, multigrooved, or re-entrant. For a material to be termed wire, however, it must be produced by drawing rods through dies or by rolling, rather than by casting or forging—and only very special shapes are rolled. As a result, thin strip and flat wire may look exactly alike, the main difference being in size.

Wire can be drawn as fine as a spider web (less than 0.004 plus or minus 0.0002 inch in diameter, the smallest standard fine wire size) or up to 0.999 inch in diameter.

Designations of Steel Wires. Commercial wire can be designated by the following styles, with the first three based on chemical composition and the fourth on the mechanical style or by the two basic quality designations.

1. *Low-carbon wires* include the nonresulfurized AISI grades 1005 through 1012, B1006 and B1010.
2. *Medium-low-carbon wires* range from AISI grade 1013 through 1022.
3. *Medium-high-carbon steel wires* include AISI grades 1023 to 1041.
4. *Special purpose wires* include both high- and low-carbon steels. Their properties are based on a combination of mechanical-mill manufacturing techniques with selected chemistry composition. These special wires include music and spring wire with 238,000 to 417,000 psi tensile strength.
5. *Industrial quality wire* is produced from low- or medium-low carbon steel. It is drawn directly from hot-rolled rods without intermediate heat treatment or special processing which would alter the normal properties by conventional dry drawing.
6. *Specification quality wire* is produced from low- and medium-low-carbon steel wire, but specific tensile strengths or softness limits have been developed by modification of standard wire mill practices or by heat treatment of specific steel compositions.

Steel Wire Finishes and Coatings. Finishes on wire are determined by the drawing process used. When no finish is required in the process the wire is identified as a *common dry process.* Finishes, according to the AISI wire manual, include *clean bright, extra-smooth clean bright, super finish,* and *sull-coated.* The sull coating is produced by dry-drawing wire after acid cleaning through fine sprays of water. This treatment produces a uniform, brown hydrated iron oxide coating to which is added a lime coating. The oxide and lime combination forms the lubricant base for the wire drawing.

Most of the steel wire produced are given a metallic coating to provide either protection or a decorative appearance. In particular the finer wires are given a very thin coating varying in color from that of copper through the various shades of brass to the color of tin. Copper sulfate or a copper-tin sulfate solutions produce thin coatings which are not efficient corrosion-resistant coatings.

For resistance to atmospheric corrosion, wires are galvanized, tinned, painted, electroplated, or plastisol coated. Zinc, either electrogalvanized or hot dipped, and aluminum are the most commonly used protective coatings. Zinc is predominantly used at the present time, for its application is low in cost and if the surface is broken the zinc continues to protect the steel by galvanic action.

Research on Wire-Wound Composite Materials

Investigations have been conducted in developing steel-wire filament-wrapped cylinders principally with epoxy resin systems (32). Commercial quantities in small-diameter (0.003-inch) steel wire with various types of metallic surfaces exhibiting tensile strength approximating 600,000 psi are now available. The material handles conveniently and without damage; it can be economically wound into a variety of container shapes which may have industrial usefulness. Exploring such applications, the following combinations have been fabricated: wire-epoxy, wire-polyethylene, wire-polypropylene, glass fiber epoxy (the glass fiber construction serves as comparison base).

The following information on this subject was prepared by Associate Professor F. J. McGarry and Research Engineer D. W. Marshall from the Department of Civil Engineering, Massachusetts Institute of Technology. The program was financed by National-Standard Company, Niles, Michigan (T. Pierce, O. Adler and E. Lang) (33).

Fibrous glass reinforced plastics with both polyester and epoxy matrices have established themselves as valuable engineering materials in a number of well-defined applications. To be economical, such uses must exploit the combined attributes of the material as fully as possible, presenting the best set of properties for the assigned task; familiar examples include molded monocoque boats, architectural covers with light-controlling capability, surface transport vehicles, electrical insulation, and aircraft components. The principal attributes so expressed are: strength, stiffness, low density, corrosion resistance, translucency, low electrical and thermal conductivity, formability, colorability, ease of machining, impact resistance, and general chemical inertness.

Perhaps one of the most impressive demonstrations of combined property optimization in reinforced plastics, however, lies in the field of missile and rocket casings. Here the absolute superiority of glass fiber filament-wound structures, on strength-weight and stiffness-weight criteria, has displaced metals almost completely and, as the newer practice matures, its position appears to become more firmly established. Concurrently, another, and possibly less obvious, advantage has emerged: the winding process as a general fabrication technique possesses inherent advantages and economies which are very attractive, especially when considered within the context of the widespread usefulness of articles of revolution as engineering implements. Pipes, rods, tubes, shells, spheres, tanks, cylinders—all are so widely used today that their value is beyond question, and all can be made in this fashion, with considerable design freedom. Different fiber filament-wound articles are presently being produced as shown in Tables 1.1 and 1.2 on pages 2 and 3. Both commercial and military markets exist with the original principal efforts being related to military using glass filament reinforcements. Research in the use of metal reinforcement has now been accelerated.

To achieve the superior strength-weight and stiffness-weight ratios that are valuable in missile structures, extremely strict controls must be maintained over every step in the raw material process sequence of filament winding. The glass fibers must be carefully drawn and immediately coated with special finishes to maintain their strength properties and, in all the subsequent textile operations, the harmful effects of abrasion, bending, improper yarn formation, moisture attack, uneven tensioning, and many other errors must be avoided. The placement of the yarns on the mandrel, the manner in which the resin is introduced, compounded, and cured, the design and usage of the mandrel—all these elements in the process also exert significant influences on the properties of the final product and thus necessitate close control. The result is obvious: higher costs, to the extent that the intrinsic economy of the fabrication method is seriously impaired if not actually eliminated. Even when the process is successfully executed it does not eliminate another serious deficiency present in all forms of glass employed structurally: the static fatigue effect, whereby the fracture strength of the material diminishes with increasing intervals under stress. Thus far, only stressing in vacuo is known to prevent static fatigue of glasses.

Most of the filament-wound pressure containers built to date, either missile casings or chemically resistant piping, have had to fulfill elevated temperature requirements which have necessitated the use

of highly crosslinked resins. In general, the latter are characterized by extreme brittleness. Because of this fact, the resistance to mechanical and thermal fatigue of composites based on such resins is not outstanding, even when the intricate and elaborate cure procedures often recommended for use are carefully observed. Repeated attempts have been made to produce these high-modulus, high-heat-distortion resins with a greater tensile ductility, but the gains have not been encouraging and much improvement remains to be seen. Hence the resistance of filament-wound laminates to fatigue damage also needs enhancement.

To circumvent some of these disadvantages, the following characteristics of a more satisfactory system can be cited.

1. A consistently high stiffness and strength, continuous filament reinforcement not subject to static fatigue at normal temperatures (-50 to $+150°F$).
2. A reinforcement which is not easily damaged in handling.
3. A winding process which does not need expensive control complications.
4. A resin matrix having mechanical ductility and good chemical resistance at normal temperatures.

The art of wire drawing, which has made considerable advances during the past several years, presents one alternative in the form of small-diameter steel filaments which are now available in commercial quantities. Having diameters in the 0.003 to 0.007-inch range and tensile strengths consistently close to 600,000 psi as a maximum, the 30×10^6 psi modulus wires are produced in a variety of alloys and with several different surface compositions including stainless, brass-coated, phoscoated, and plain carbon steels. Though the wires are strong they are not unusually brittle or prone to abrasion damage, and comparatively simple handling methods have no bad effects on their strength; they are easy to use in filament winding. No complicated cleaning or finishing procedures seem necessary and many available resin formulations can be used as the matrices. In this respect, the resins under investigation include not only the usual epoxies but also certain polyolefins such as polyethylene and polypropylene, which are attractive because of their excellent moisture and chemical resistance and because of their ability to deform appreciably before tensile or shear fracture. They possess considerable mechanical ductility.

Thus the research has been concerned with the properties of wire-epoxy and wire-polyolefin filament-wound laminates as compared to fibrous glass-epoxy and fibrous glass-polyolefin ones. Initially, the

adhesion between resin and wire had to be studied and optimized. Then flat laminates laid up by filament-winding methods were evaluated. Next, the simple NOL ring has been useful as an evaluation method leading to the best combination of parameters for thin-wall tubes and pipes.

Bikerman (34) points out that the achievement of a proper joint realizes the known cohesive strength of the weaker component, in the absence of other materials having inferior strength properties; such was the controlling philosophy in this phase of the work. A very simple test system was the experimental tool. A 1-inch resin disk cast into a Teflon mold, containing a 0.010-inch-diameter axially positioned wire, provided a pull specimen in which the joint was subjected to shear stressing on a gross scale. To be found were the proper wire cleaning methods to give best adhesion on plain carbon steel filaments with: (*a*) a plated brass coating; (*b*) an inorganic-based liquor coating; and (*c*) a phoscoated surface resulting from an acid etch. Some of the resins first used were:

Epoxies	Polyolefins *
1. Epon 828, Curing Agent Z 1 hour at 212°F	1. Marlex 6002 polyethylene 1 hour at 390°F
2. Dow Novalac X2638.6 Curing Agent Z 1 hour at 225°F	2. Tenite 3440A polyethylene 1 hour at 390°F
3. Araldite 6020 Curing Agent Z 1 hour at 212°F	3. Hercules 6511J polypropylene 1 hour at 450°F, under nitrogen
	4. Epolene N, polyethylene wax

* Treated to become adhesionable as described in reference (35)

Two methods of wire cleaning were explored. The first consisted of exposure to toluene vapor for several minutes—essentially a simple degreasing operation—and the second preceded the vapor treatment by polishing with an aqueous alumina suspension which was immediately rinsed by distilled water. As is evident from data for the 828(Z) resin, the mechanical removal of surface oxides prior to vapor degreasing optimized the joint strengths with all three surfaces, though the degree of improvement was variable; the proper joints averaged about 3,500 to 4,000 psi breaking stress while the other epoxies were somewhat lower, in the 2,500-psi range. (The latter formulations are heat-resistant polymers and probably require a higher-temperature cure to develop their maximum strengths which are comparable to

that of the 828(Z) resin.) An interesting point lies in the relatively small improvement produced by mechanical cleaning of the phoscoated wire. Metallographic study of this surface indicated that it was much rougher than either the brass or liquor finishes and, as a consequence, the weak oxide layer along the surface was not sufficiently planar to permit the fracture to localize along this zone of lower strength. A completely analogous situation was encountered some time ago with glass rod-polyester disk tests, using smooth as opposed to etched rod surfaces (36).

Of the other wire finishes only some samples of the liquor wire showed any appreciable surface roughness, and this was considerably less than that of the phoscoated. The liquor wire is not inherently or consistently rougher than the brass wire, however, because all are drawn by identical methods. Apparently the particular batch used in these tests came from a slightly worn drawing die, since other samples of liquor wire subsequently examined showed no such greater roughness; the data suggest that the test method is sensitive to such influences.

With the polyolefin adhesives, vapor degreasing was necessary but

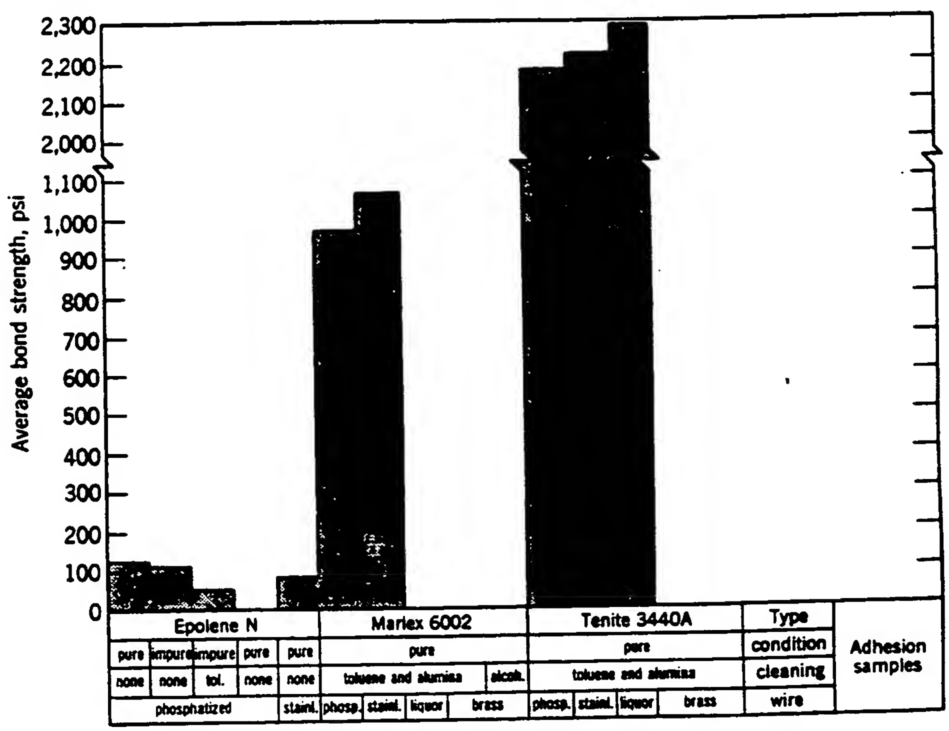


Figure 3.5 Average bond strength vs. resin, surface, and cleaning (33).

not sufficient to produce good bonding; very thorough mechanical cleaning followed by the water rinse and the toluene vapor treatment were all needed to form proper joints. Epolene N is a low molecular weight wax-type polymer which was used in preliminary work simply because of its ease in handling, and therefore the low joint strengths presented in Figure 3.5 merely reflect the low cohesion of the bulk material. The linear, high-density Marlex 6002, on the other hand, adhered well to stainless and phoscoated wires and not so well to the brass and liquor finishes; the latter can probably be explained on the basis of a rapidly formed layer of weak copper oxide on these wires which, incidentally, is soluble in the amine curing agent used with the epoxy resins where its effect was not evident. Another linear, high-density polyethylene, Tenite 3440A, showed the highest bond values and the oxide effect with the liquor finish was not present. This difference in the behaviors of the two polyethylenes may be caused by physical rather than chemical actions: when molten, the viscosity of the 3440A is considerably less than that of the 6002 and, as a consequence, its ability to intimately wet the very rough phoscoated wires, and the somewhat smoother liquor-finished ones, is much better. As a matter of fact, the melt viscosity of the 6002 is great enough that pressurization of the disk molds was necessary to produce joints that could be tested; without the pressure, bonding was not achieved.

Adhesion work with a variety of polypropylene resins was discouraging, because of the polymer's strong proclivity toward oxidative degradation above its melting temperature, which becomes even more pronounced, indeed catalyzed, by the presence of the metal surfaces being used. Bulk properties of the resin indicate that joint strengths of the order of 2,500 to 3,000 psi should be possible, but the best results ever achieved have been in the vicinity of 500 psi, and attempts to suppress the problem by using antioxidants have not been successful. With no antioxidant, working in air, in vacuo, or under nitrogen, simply no adhesion can be effected; with the antioxidant, the joints are unacceptably weak, as indicated. No good solution to the problem has been found to date.

To produce filament-wound laminates, a simple winding apparatus was designed and constructed. When using wire reinforcement, as in Figure 3.6, the 50 filaments are drawn from individual spools, gathered into a flat tape at the input end, passed through a pair of opposed rotation fabric buffing wheels wet with alumina-water suspension, rinsed in a distilled water tank, make several traverses in the boiling toluene chamber, pass through the resin pot, and are wound onto the

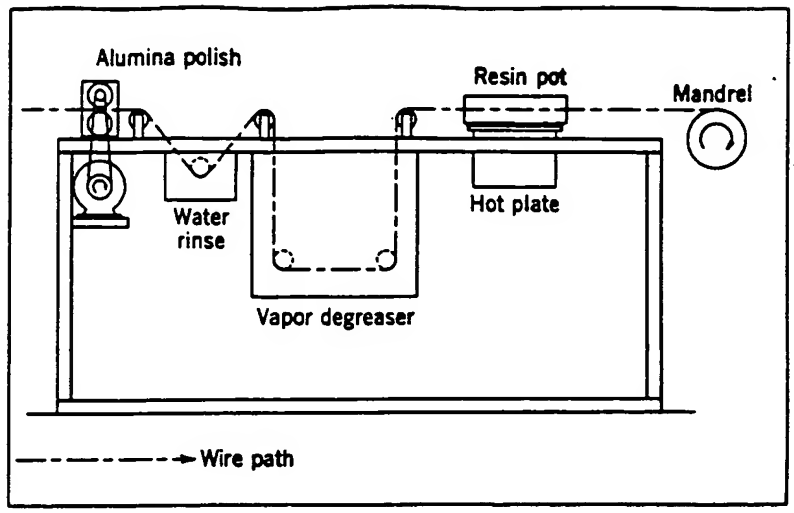


Figure 3.6 Cleaning sequency-wire reinforcement (33).

mandrel. Fibrous glass, prefinished, goes directly from the spools to the resin pot.

The device is a moving mandrel and stationary feed type; both the rotation and translation of the mandrel are independently powered through simple gear-clutch-cam systems, so a wide variety of speeds and pattern angles are available, facilitating the fabrication of many different kinds of laminates. The amount of resin pickup is also simply but effectively controlled by a combination of two schemes; resin viscosity is altered by temperature or by diluents, either polymeric or solvent, and the size of the exit orifice from the resin pot is adjusted by a screw-controlled dam plate. The pot can also be pressurized, or filled with an inert gas, if desired.

To prepare flat, unidirectional laminates, an 18-inch-diameter sheet-metal drum mandrel is used; it has an axial slot on its outer periphery which permits cutting the windup, usually composed of four to six thicknesses, and flattening of it for press curing. Tensile and flexural specimens are then prepared and tested in accordance with ASTM specifications. Many different resin-reinforcement combinations have been explored in this fashion, and the best results achieved to date are presented in Table 3.10. Such data are based upon multiple laminate samples which are known to be representative, and therefore the following observations can be offered with confidence:

1. The glass fiber–828 laminates made by this method show no loss of properties after a 2-hour water boil or after a 30-day room temperature water-immersion period.

Table 3.10 Steel-Wire Laminated Data

Reinforcement *	Content	Resin	Cure	Flexural		Tensile	
				Modulus, 10^6 psi	Strength, psi	Modulus, 10^6 psi	Strength, psi
I. Phoscoated Steel (vapor cleaned)	70% by volume	50 pts 828 50 pts Araldite 6005 20 pts Agent Z	30 min. 220°F 200 psi 2 hrs. post at 300°F	12.80	2.46×10^5	19.7	4.28×10^5
II. Brasscoated Steel (vapor cleaned and polished)	70% by volume	50 pts 828 50 pts Araldite 6005 20 pts Agent Z	30 min. 220°F 200 psi 2 hrs. post at 300°F	15.24	3.18×10^5	21.2	N.A.
III. Fibrous E-glass 60 end roving, 801 finish	84% by weight	100 pts 828 20 pts Agent Z	30 min. 220°F 200 psi 2 hrs. post at 300°F	7.41	2.19×10^5	7.4	N.A.
IV. Phoscoated Steel (vapor cleaned)	70% by volume	Polyethylene: 50 pts Alathon 10 30 pts Tenite 808A 20 pts Epolene N	20 min. 350°F 200 psi Press cooled	2.98	6.07×10^4	14.8	3.60×10^5

* The phoscoated and brass wire used here had tensile strength of 575,000 psi.

2. Extreme difficulty in machining the wire-based laminates has been experienced; indeed the material is almost impossible to cut without edge damage. Thus, the values from the test samples are believed to be on the lower side.

3. With the wire-epoxy laminates noted in Table 3.8, the resin blend was used to reduce the room temperature viscosity and to control resin pickup. If only 828 is used, either elevated temperatures or solvents must be employed for the same purpose.

4. The viscosity of molten polyethylene is high enough to make this method of type or yarn impregnation very difficult and, thus far, the behavior of fibrous glass yarns has been unsatisfactory; because the drag of the molten resin repeatedly causes filament breakage, no such laminates have been so prepared. Even with the more manageable wire filaments, it is necessary to blend the best polyethylene with lower molecular weight formulations to depress the viscosity adequately.

5. The use of polyethylene instead of epoxy as a matrix severely reduces the mechanical properties of the laminate in flexure where interlaminar shear actions are operative. It should be noted, however, that where the brittle resin laminates actually fracture at their maximum stresses, the polyolefin ones do not, merely continuing to deform or flow with no resin-reinforcement separation or fracture, after the maximum load is reached. This suggests a fundamentally different pattern of mechanical behavior which may have value in certain applications.

6. Another limitation of the polyolefins as laminating resins is their low softening temperature; as mentioned previously, this has not been regarded as a critical deterrent, but improvements are desirable. To explore one remedy, the use of cross-linking agents has been investigated, with the results shown in Figures 3.7 and 3.8. From these it has been determined that while some benefit is gained the linear high-density resins remain superior, though attempts at crosslinking to further improve them have not been successful.

Applications of wire-wound articles where weight is an important factor can be visualized—a reusable container for shipping gas under pressure, for example. For this reason, the data in Table 3.11 are interesting; they refer to the same materials described in Table 3.10 and compare the E-glass and brasscoated laminates in terms of properties per unit weight. It may be argued that the glass laminate is not representative of the best that can be realized with this kind of reinforcement and, hence, the comparison is unfair, but a valid rebuttal

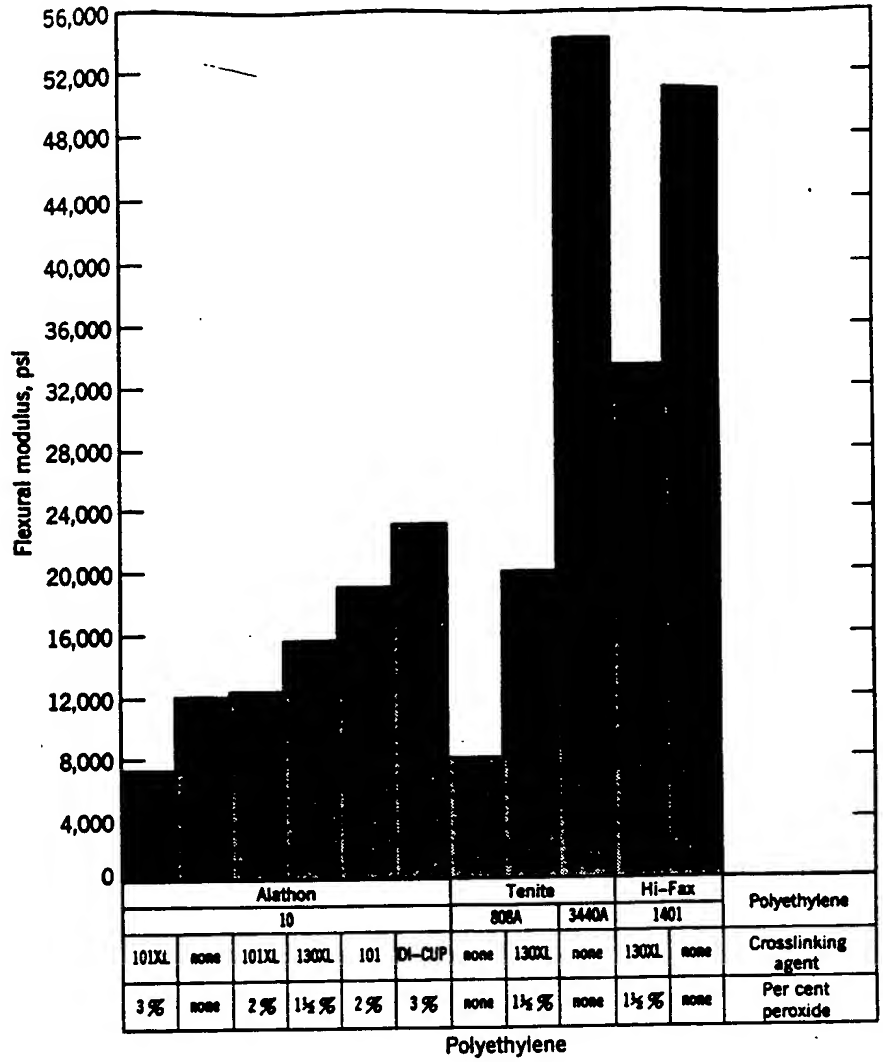


Figure 3.7 Polyethylene flexural modulus at 130°C (33).

stems from the static fatigue factor mentioned earlier. Higher-strength glass laminates can be prepared but their degradation with time under stress is significant and does not cease, so taking this fact into account makes the data in Table 3.11 both realistic and useful, it is believed.

The NOL ring test was developed to provide a laboratory simulation of filament-wound structures for research and development purposes; the method continues to undergo modifications and refinements, but the technique used in this study is an early, simple version. The reinforcement is wet-wound on a split disk, and then the composite is cured by continued rotation of the disk under radiant heat sources.

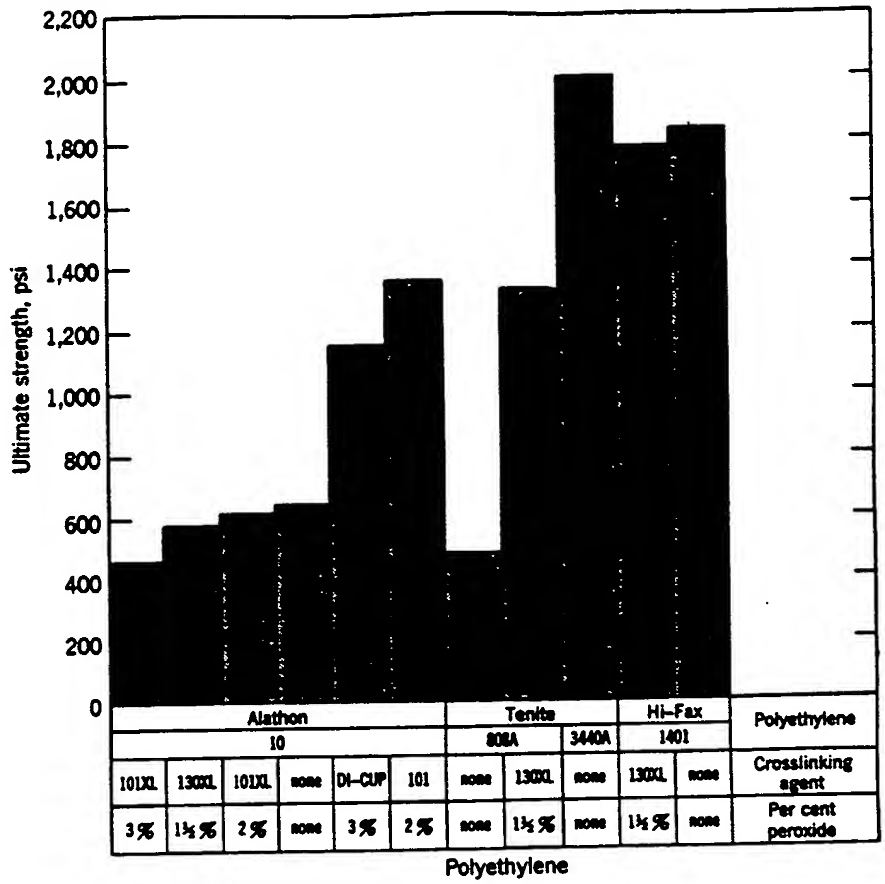


Figure 3.8 Polyethylene flexural strength at 130°C (33).

***Table 3.11** Comparison of Laminates II (Wire) and III (Glass)*

Density II	0.1765 pounds/inch^3
Density III	0.0744 pounds/inch^3
Specific tensile modulus III *	0.998 $\times$ 10^8 inches
Specific tensile modulus II *	1.20 $\times$ 10^8 inches
Flexural moduli ratio II/III	2.05
Flexural strength ratio II/III	1.45
Tensile moduli ratio II/III	2.83

* Ratio between tensile modulus and density of the laminate.

After the cure has been completed, the halves of the disk are pulled apart in a tensile testing machine and the fracture load observed; failure usually occurs in that portion of the ring adjacent to the disk separation, suggesting that the combined actions of tension and flexure present there are responsible for the breaks. The failure stress is referenced to the amount of reinforcement present in the ring, rather than to the gross cross section of the composite, since by so doing a better indication of the utilization of the reinforcement is established. Table 3.12 shows such data for various combinations of wire resin and glass resin; in all instances the averages are based upon multiple tests in which only a small amount of scatter was present. It can be seen that by flexibilizing the resin matrix, substantial improvements in reinforcement performance are achieved; if this process is followed too far, however, the wire stress decreases again, and with the relatively soft polyethylene, the wire cuts through the resin when the ring is loaded and shows strengths about the same as with a dry ring containing no resins at all. With the proper degree of resin ductility in

Table 3.12 Steel-Wire and Glass-Laminate Data

Reinforcement	Resin	Stress in Reinforcement, at Failure, psi
Phoscoated Steel	828–20 parts Z	325,000
	70 parts 828 30 parts X71 10 parts DTA	427,000
	50 parts 828 50 parts X71 10 parts DTA	428,000
	70 parts 828 30 parts Versamid 140	428,000
	Polyethylene	319,000
	828–80 parts NNA	360,000
HTS Roving	828–20 parts Z	250,000
	70 parts 828 30 parts X71 10 parts DTA	330,000
	50 parts 828 50 parts X71 10 parts DTA	324,000

the epoxy systems, 75 per cent of the tensile capacity (430,000 psi) of the wire has been realized and perhaps this may be further improved by better winding and testing procedures.

TAPES

The tape-winding process consists of winding a tape onto a mandrel of the desired configuration. In the application for re-entry space vehicles the tape is wound on a mandrel under tension in a continuous operation from the stagnation region to the conical base of the re-entry body; the laminations are parallel to the longitudinal axis. Tape winding is also easily adapted to cylindrical shapes. Cost probably contributes more to the motivation of the development of tape-winding processes than any other factor. Where tape winding can be applied it is generally expected that costs will be reduced and strength properties will be increased when compared to filament winding or other techniques.

The tape-winding process is similar to the convolute tube winding process, which is presently being used to make insulators and coil forms for the electrical industry. A hot roll is used to melt the resin on the impregnated reinforcing material or the adhesive for metal tapes just before it is wound on a mandrel. Pressure is applied to

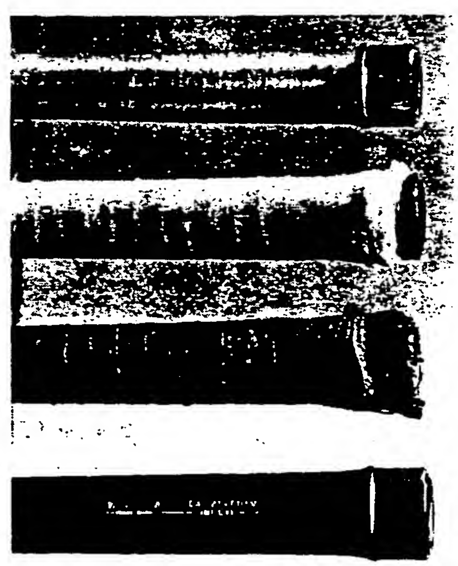


Figure 3.9 Stages shotgun manufacture; filament wound, convolute wrapped, impregnated, and finished barrel. (Courtesy of Olin Mathieson Chemical Corp.)

this mandrel, as it contacts the mandrel by the hot roll, which is connected in turn to a pressure cylinder. Tension is applied to the impregnated material, as it is being wound, by a tension device such as a friction brake.

The rolling or winding speeds that apply for convolutely wound tubing also apply to the tape-winding process. The curing also takes place on a mandrel in an air-circulating oven or other suitable compartment. Curing problems can be more complicated for certain shapes. For example, in a conical re-entry vehicle curing lap-wound parts is somewhat more involved because the compressive forces created during the cure tend to push the part from the mandrel.

Metal Tape

Steel tapes or strips are being evaluated as potentially efficient materials for producing rocket motor bodies (37). The ultra-high-strength metallic tape is helically wound around a mandrel by a ribbon wrap–plastic bonded process. Various companies are now developing this type of product (38).

One basic problem confronting metal-tape wrapping is that only straight cylindrical tubes or conical shapes can be produced. Any compound curve in the design is either impractical or impossible. End closures will probably have to be adhesively bonded by means of such techniques as scarf or double-lap joint systems (39).

Government agencies and industries are presently in search of new approaches to lightweight, high-strength solid rocket motor cases. Investigations use high-strength steel-bonded cases based on metal design allowables up to 350,000 psi (50). To accomplish this end, various structural adhesives have been evaluated, process techniques have been developed, and motor case scale models have been built and tested.

Tests have shown that conventional adhesives can function in a solid rocket motor case in which the metal adherent is stressed to 250,000 psi. To improve this value even further the adhesive should be designed so that its shear modulus varies along the bonded joint. Varying shear modulus adhesives have been prepared, with the preliminary results indicating a 25 per cent higher load-carrying capability.

Plastic Tape

Research, development, and actual production has been in existence using reinforced plastic or nonmetallic tapes. In order to de-

velop maximum strength properties, principally unidirectional preimpregnated glass fiber tapes are used. Where a combination of strength and heat resistance are required, preimpregnated asbestos papers have been used. Tapes with different basic fibers can be used to produce thermal insulation barriers and make available high-strength or modulus raw materials. See Table 3.8 for examples of various fibers.

A typical example using "prepreg" glass fabric tape in continuous manufacturing processes involves corrosive and submarine pipes. Tape-wrapped pipes up to 60 inches in diameter and 12 feet in length are being produced (41).

Resin-impregnated unidirectional glass tapes have found many and

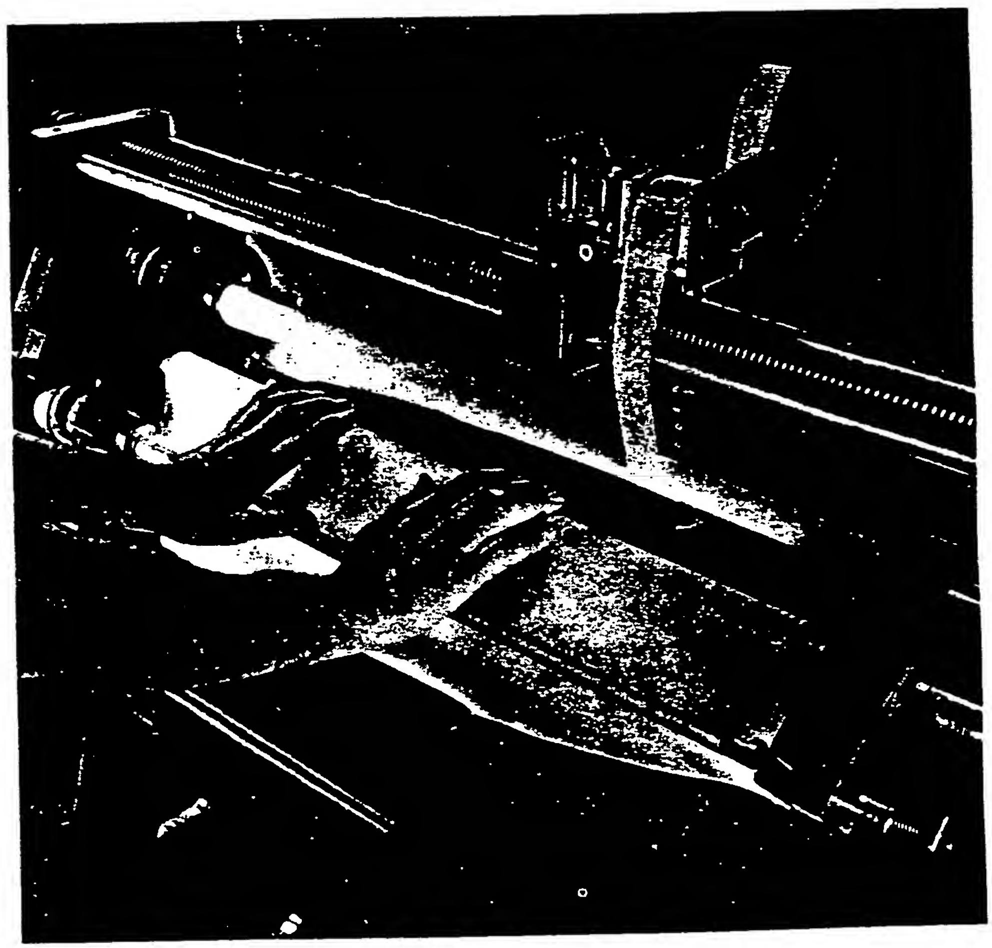


Figure 3.10 Convolute glass cloth tape wrapping operation in shotgun barrel manufacture. (Courtesy of Olin Mathieson Chemical Corp.).

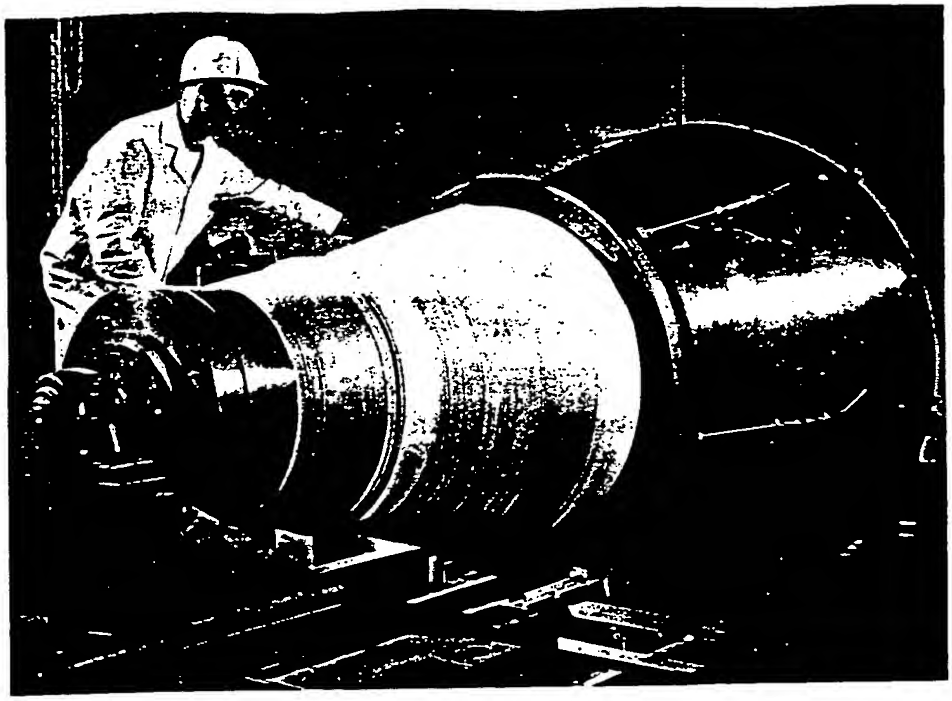


Figure 3.11 Asbestos-phenolic tape wrapped motor exit cone liner. (Courtesy of Thompson Ramo Wooldridge, Inc.)

varied uses. A typical tape or ribbon assembly involved 20 ends of roving held together with the preimpregnated resin. The rovings are kept parallel to each other and in one layer. The width of this type of construction is approximately ⅛ inch or more. The ⅜-inch-wide ribbons consist of 3 x 20 end roving.

The most common resin used to date is a polyester which, after proper cure, enables development of ultimate tensile strengths in wrapped bands of up to 160,000 psi (based on total cross section) (42). The polyester prepreg tapes have found extensive use in binding the windings of rotating electrical equipment.

Another interesting reinforcement is to use flat-sided glass fibers. These flat fibers may result in stronger reinforced plastic structures. Several glass hoops 18 inches in diameter tested to destruction in a study (43) showed that the failure in each case occurred in the non-glass region of the hoop. Flat filaments would make possible nearly 100 per cent glass content and yet allow uniform bonding area between filaments.

Refer nces

1. J. B. Rittenhouse, W. G. Jurevic and E. E. Morris, SAMPE Symposium, Section 19 (June 1963).
2. R. J. Runck and B. W. King, Battelle Memorial Institute (June 1961).
3. J. S. Islinger, K. Gutfreund, R. G. Magure, and O. H. Olson, WADC TR 59-600 (March 1960).
4. T. Kozlowski, *The Glass Industry,* 41, 324 (June 1960).
5. E. B. Shand, *Glass Engineering Handbook,* 2nd Ed., McGraw-Hill Book Co., New York, 1958, p. 375.
6. S. Brelant and M. Varlas, SPE Annual Technical Report, P. 8–1 (January 1962).
7. W. J. Eakons, W. G. Camp and D. Wetherbe, DeBell of Richardson, Inc.
8. I. Skiest, *Adhesives,* 1st Ed., Reinhold Publishing Corporation, New York, 1962.
9. W. J. Eakons, SAMPE Preprint, p. 1 (March 1961).
10. P. Layton, SAMPE Preprint, p. 197 (1961).
11. Development Work on Improved High-Modulus Structural Glass Fiber, Imperial Glass Corporation, Navy Contract NOa (S)55-213-C (January 1957).
12. G. P. Peterson, SPI Annual Reinforced Plastics Preprint, p. 1A (February 1962).
13. G. P. Peterson, SPI Annual Reinforced Plastics Preprint, p. 1A (February 1962).
14. P. W. Erickson, F. R. Barnet, H. A. Perry and S. Karpe, SPI Annual Reinforced Plastics Preprint, p. 1B (February 1962).
15. "Fiber Optics in Aerospace Vehicle Hazard Detection," ASD-TDR-62-731, December 1962.
16. P. Layton, SAMPE *Meeting Report,* p. 197 (March 1961).
17. G. P. Peterson, SAMPE *Meeting Report,* p. 316 (March 1961).
18. W. H. Otto, SAMPE *Meeting Report,* p. 32 (March 1961).
19. W. W. Drummond and B. A. Cash, WADC TR 59-699 (March 1960).
20. A. H. Lasday, "Development of High-Modulus Fibers from High Temperature Materials," Houze Glass Corporation (1958).
21. A. M. Shibley, H. L. Peritt and M. Eig, SPI Annual Reinforced Plastics Preprint, p. 6A (February 1962).
22. H. Bernstein and J. A. Kies, SAMPE *Meeting Report,* p. 273 (March 1961).
23. D. V. Rosato, ACS St. Louis Meeting, Nonwoven Fabrics Symposium (March 1961).
24. D. V. Rosato, *Asbestos,* 1st Ed., Reinhold Publishing Corporation, New York, p. 59 (1959).
25. *Fibrous Glass,* U.S. Dept. of Commerce (October 1961).
26. F. Fechek and M. Hennessey, AIAA Report 2926-63 (April 1963).
27. W. E. Rumbles, SAMPE *Meeting Report,* p. 122 (March 1961).
28. W. O. Everling, "Super High Strength Wire," 6th Sagamore Ordnance Material Research Conference, Syracuse University Research Institute (August 1959).
29. "Naval Ordnance Laboratory Develops Test Blast from Small Charges in Cones," News Release, DOD, Office of Public Affairs, Washington, D.C. (August 3, 1960).

30. D. V. Rosato, *Ind. and Eng. Chem.*, **54**, No. 8, p. 31 (August 1962).
31. J. W. W. Sullivan, *Material in Design Engineering*, **57**, No. 6, p. 71 (June 1963).
32. B. F. Goodrich Co., *Filament Wound Bull.*, 1-87010K672 (1961).
33. F. J. McGarry and D. W. Marshall, SPE-RETEC Birmingham Section (September 1962).
34. J. J. Bikerman, *The Science of Adhesives Joints*, Academic Press, New York and London (1961).
35. J. J. Bikerman, *Adh. Age*, p. 23 (February 1959).
36. "Bond Studies in Glass Reinforced Plastics," MCA-MIT Plastics Research Progress Report (October 1957).
37. Composite Materials and Structures, 6th Sagamore Ordnance Materials Research Conference, p. 366, Syracuse University Research Institute (18 August 1959).
38. *American Machinist/Metalworking Manufacturing*, **103** (27 January 1960).
39. *American Machinist/Metalworking Manufacturing*, **103** (27 January 1960).
40. S. J. Dastin and P. Rosenberg, "New Techniques in Bonding Solid Fuel Rocket Motor Cases," SAE National Auto Week (13–17 March 1961).
41. A. L. Wester, SPI Annual Preprint, pp. 15D–1 (February 1962).
42. A. G. Pehrson, SPI Annual Preprint, pp. 2B–1 (February 1962).
43. DeBell and Richardson, Inc., "Improved Strength on Wound Structures," OTS-AD-278121, Washington, D.C. (1961).

4 Resinous Matrices

The term resinous matrix denotes the material used to envelop the reinforcement. Even though the major load in the filament-wound structure is carried by the reinforcement, the matrix is a critical and important part of the structure. With an improper choice or application of the resin desired strength properties cannot be achieved. The term resin is used to refer to a solid or semisolid material of natural or synthetic origin, and of organic or inorganic nature. It usually exhibits no definite melting point and is often amorphous in structure. The noun plastic is used in the engineering sense to define a mixture of resins, with fillers or reinforcements and other ingredients suitable for further processing into a fabricated article. Resins are sometimes confused with polymers, since many important matrices consist of polymeric resins. In this context, the binding material will be termed a matrix (or a resinous matrix) which envelops and holds the reinforcement in place.

It might be better understood if one spoke of the four principles of direct pertinence in reinforced plastics utilization (1). The overall mechanical strength depends on the combined effect of the amount of reinforcement and its arrangement in the finished article. The chemical, electrical, and thermal performances result from the choice and formulation of the resinous matrix materials. The materials selection, with design and production requirements, determine which process of fabrication is most desirable. Finally, the economical cost and quality of performance result from good design and proper choice of reinforcement and matrix.

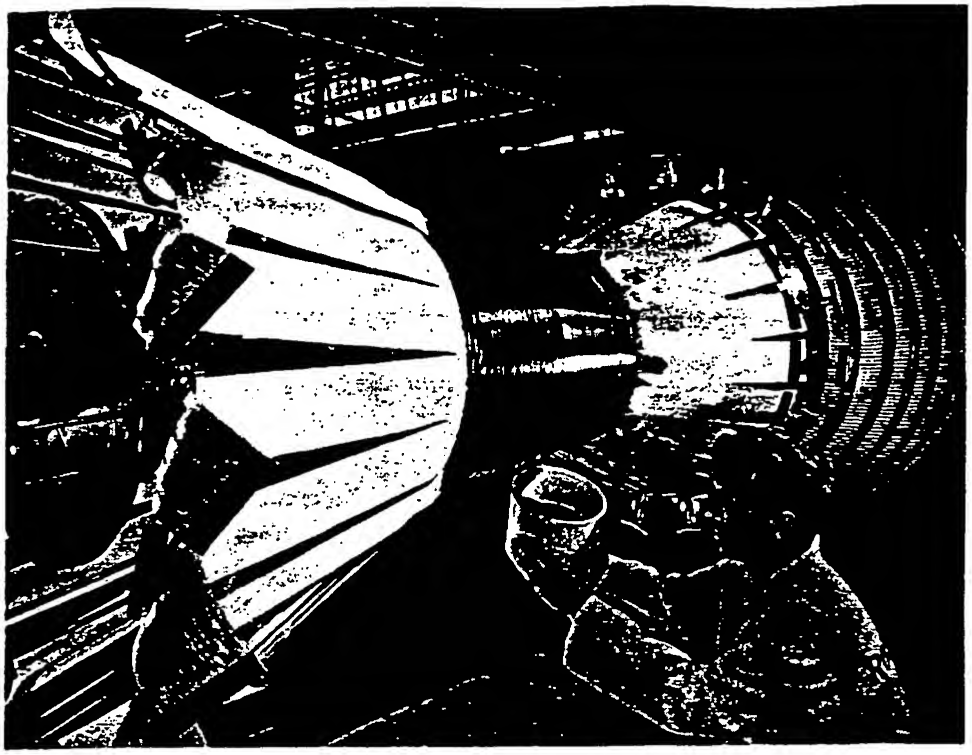


Figure 4.1 Atlas rocket engine-booster thrust chamber incorporating longitudinal glass roving tapes with glass fiber axial wrappings and excess resin. (Courtesy of NAA Rocketdyne.)

The major resins used in a filament-wound structure vary in resistance to corrosion and heat. Performance of a given resin can be changed by formulation of ingredients, such as filler, pigment, and catalyst systems. For general reinforced plastics, polyesters comprise a large percentage of the total because they are economical. Other resins in use are epoxies, phenolics, silicones, melamines, acrylics, and polyesters modified with acrylics. For filament-wound structures, heavy emphasis has been placed on the epoxies.

In developing, maximum strength properties, the aim is to apply a minimum amount of resin. The amount is dependent on the space available between fibers. When fibers are closely netted, the available volume to be filled by the resin can be predetermined. In addition to having the resin occupy this volume, an extremely thin layer of resin is required between mating or adjoining fibers. The thickness of this separating film is usually less than .0001 inch. When the proper finish is applied to the reinforcement, resin completely covers the fiber surfaces. The resin matrices used are designed specifically

for filament-wound composites. The resin provides strong bonds to the reinforcement, produces high shear strength and has an elongation of approximately 1 to 2 per cent so that it can match the glass reinforcements.

When the concept of glass-resin filament winding was initiated approximately a decade ago, polyester-resin systems were used. At that time polyesters accounted for about 85 per cent of all resins consumed by the glass-reinforced plastics industry. During the interim period, epoxy resins have almost completely displaced polyesters for filament winding. It is estimated that over 90 per cent of the resin used presently in filament winding is the commercially available bisphenol A-epichlorohydrin epoxies.

When polyesters are compared to epoxies, they are found to be more brittle and to provide a lower-strength bond to the glass fiber. Phenolic resins have also been introduced into filament winding since they basically exhibit higher temperature resistance and are lower in cost. The latter structures are not as strong at room temperature. In selecting a resin matrix for filament winding, processing characteristics of the system are very critical. Much production today is by the wet-winding technique. The resin is liquid at room temperature with a low viscosity ranging from 500 to 1,000 cps. The desired pot life (before resin gels or hardens) has to be long enough in order to complete the winding operation. In general, an 8-hour working life is desired. Another important characteristic for the resin is that it contain 100 per cent solids.

The epoxy resin systems can meet these requirements (2). They basically meet the viscosity and pot life requirements. These give good wetting of the glass filaments and help maintain a uniform resin content throughout the structure. New epoxy-resin systems are presently being developed to further improve processing characteristics. These resin developments (epoxy, phenolics, etc.) are proceeding at a rapid rate, since they are useful and desired in many other plastic products (3).

EPOXY RESINS

The epoxy resins are among the newest of the major industrial plastic materials. They are thermosetting, and when converted by a curing agent these resins become hard, infusible systems. Although there are a number of possible reactants and a wide variety of possible epoxy-resin molecules, there are only a few resin types (4) of commercial significance in the United States. Of these the condensation

product of epichlorohydrin and bisphenol A or bis (4-hydroxyphenyl) dimethylmethane is of major importance (5). This resin system is cured by reaction with organic amino or acid compounds.

These thermosetting resins have superior chemical resistance, good adhesion, very low water absorption and cure shrinkage, good electrical properties, and high strength (6). These inherently superior characteristics compensate for their higher cost in comparison to other resin systems. Use of epoxies for general types of reinforced plastics has in the past been limited to critical applications where the materials' superior properties were required. However, with the development of filament-wound structures and the advantages of using epoxy resins, they have found many new applications. Processibility in properties of a reinforced epoxy material are highly dependent on the type of hardener used to cure it. Aliphatic amines provide optimum handling characteristics. Aromatic amines provide good short-time heat resistance. To develop more flexibility, vegetable oil polyamides are used.

Epoxy-resin systems are generally limited to a temperature of approximately 300°F (7). Recently higher-heat-resistant epoxy resins have been produced. The epoxy-novolac resins have been tested up to a temperature of 750°F using the Naval Ordnance Laboratory (8) hydrostatic test procedure. After aging 5 minutes at 750°F, tensile strengths and interlaminar shear strengths of 100,000 psi are reported. After 2 hours aging at 500°F, tensile strengths of 140,000 psi and interlaminar shear strengths of 3,500 psi were developed. Room temperature properties for these glass yarn-resin rings were 190,000 psi for tensile strength and 9,000 psi for interlaminar shear strength.

Epoxy resins can be used either by wet winding or by preimpregnated roving. There are advantages and disadvantages for each method. A recent development has been an epoxy-glass prepreg roving for filament winding, which produces high-quality performance characteristics coupled with processing ease. Table 4.1 gives some of the physical properties of this material (9).

The hybrid character of the epoxy-novolac resins make them well-adapted for consideration in the high-temperature filament-winding resin. Types are available containing a phenolic backbone for improved heat resistance along with epoxy groups for curing and cross-linking without the release of volatile products. The ASTM heat-distortion temperature value of 568°F can be obtained. This is very high for any resin system. The resin viscosity is 17,000 cps at 77°F, 6,200 cps at 88°F, 4,400 cps at 97°F, 2,000 cps at 113°F, 740 cps at 130°F, and 400 cps at 140°F. At room temperature, the resin is

Table 4.1 Physical Properti s of Filament-W und NOL Rings

Filament-Wound [a]	HTSE Glass	S994 Glass
Tensile Strength (NOL Ring, average fiber stress)	385,700 psi [b]	475,000 psi [b]
Tensile Strength (NOL Ring, average composite stress)	274,000 psi [c]	336,500 psi [c]
Tensile Strength (Burst Strength)	7,000 pounds	8,200 pounds
Interlaminar Shear (Segmented Ring)		
Dry	11,300 psi	
After 6 hrs. boil	10,400 psi	
Compression Fist (NOL Ring, A. O. Smith Procedure)	197,000 psi	
Resin Content	22–24%	22–24%
Void Content	3.16	3.16
Resin Specific Gravity	1.18	1.18
End Count of Glass	20	20

[a] All procedures per Federal Specification LP-406B.
[b] Standard deviation 5084.
[c] Standard deviation 3713.

heavier than the conventional epoxy. This heat-resistant epoxy has been handled at room temperature to obtain good properties. However, it can be more suitably handled in production by applying the resin when it is slightly heated. Some of the winding machines contain controlled heat chambers for use with this resin.

Other development programs to improve the heat-resistant property of epoxy resins have involved the use of new hardeners, such as peracetic acid (2). Modifications of the resin are being made so that improved techniques can be utilized during manufacture of filament-wound structures. Close controls are made in regard to viscosity, heat-distortion point, pot life, and basic strength properties.

Epoxies continue predominant as the matrix in filament-wound structures. Any available data on the cast resins properties, such as density, hardness, shrinkage on cure, elongation, heat distortion temperature, shear strength, tensile strength, flexural strength, and compressive strength are useful in selecting a resin for filament winding. However, the particular filament-wound structure governs the most useful of the cast resin properties (10).

Based on a large number of studies under government contract, a proposed specification of a high-temperature resin to be used in filament winding was developed (7 and 10). The property requirements

are based on those of the resin and those of a composite unidirectional filament-wound ring. Table 4.2 lists some of these recommended specifications.

POLYESTER RESINS

The term polyester resins encompasses a variety of materials. By virtue of usage the major useful compositions are the unsaturated polyester resins which are easily handled and fabricated. Polyester resins are readily reinforced with fiber glass and other reinforcements, leading to broad utilization in many reinforced structural items. Polyester resins were used in the early development of filament winding but gave way to epoxies for military usage. However, various commercial filament-wound items still depend heavily on polyesters.

The polyester resins are the polycondensation products of dicarboxylic acids with dihydroxy alcohols. Maleic and fumaric acids are the chief unsaturated acids used. The principal dihydroxy alcohols used are ethylene, propylene, diethylene, and dipropylene glycols. These resins have the ability to cure or harden at room temperatures under no pressure or low pressure when catalyzed with such compounds as methyl ethyl ketone peroxide, plus cobalt naphthenate. The presence in the formulation of cross-linking agents such as styrene results in resins which are thermosetting and insoluble-infusible when fully cured.

Table 4.2 Proposed Resin Specification for Elevated Temperature Resistant, Filament-Wound, Glass Reinforced Composites

Physical Properties of Resins	
Viscosity, centipoises, maximum at winding temperature	2,500
Shelf life, uncatalyzed, months, minimum at room temperature	12
Pot life, catalyzed, hours, minimum at winding temperature	12
Cure temperature, °F, maximum	500
Cure time, hours, maximum	16
Heat distortion temperature, °F, minimum	475
Mechanical and Physical Properties of Unidirectional Rings	
Ultimate hoop tensile strength, psi	150,000
Ultimate hoop tensile strength after 2-hour boil	95% of control
Initial modulus of elasticity, psi	7.3×10^6
Interlaminar shear strength, psi	7,000
Specific gravity	2.0 ± 0.2
Glass content, per cent by weight	80 ± 2

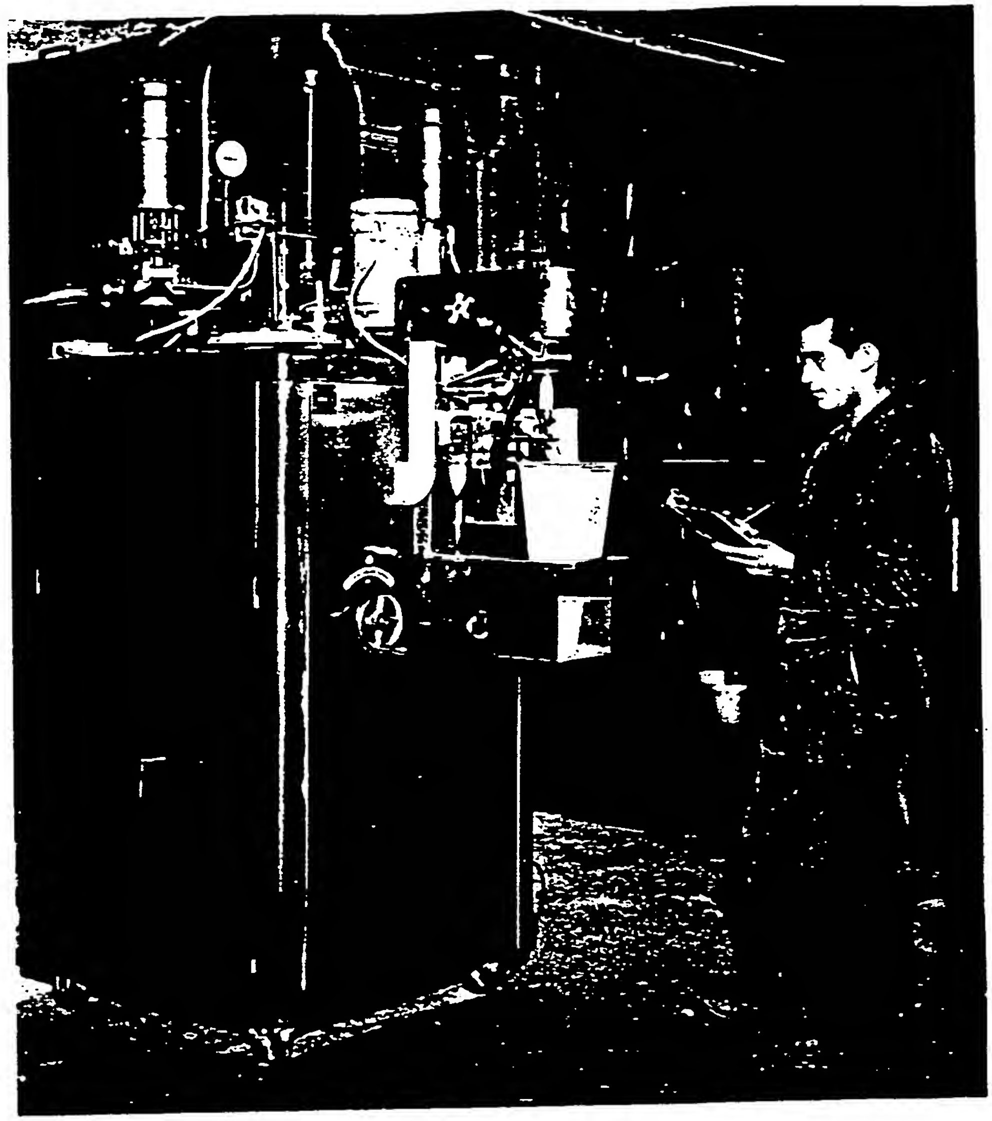


Figure 4.2 Three-component epoxy resin mixer and dispenser. (Courtesy of Lamtex Industries, Inc.)

A limited amount of polyester resins are being used in filament-wound military structures. One major application for modified polyesters is in aerospace radomes. The resin is modified with triallyl cyanurate (TAC). This resin system provides a low dielectric constant and loss factor which is required in order to develop radar transparency. The TAC modified system can be used up to temperatures of 500°F, as compared to conventional polyesters which tend to weaken above 250°F.

Table 4.3 Physical Pr perti s of Cur d Polyester R sins

	ASTM Test Method	Rigid Cast R sin
Fl xural Strength, psi	D 790	8,500–18,300
T nsile Strength, psi	D 638	6,000–10,000
Tensile modules, psi $\times 10^5$	D 638	3.0–6.4
Tensile elongation, per cent	D 638	<5
Compressive Strength, psi	D 695	13,000–36,500
Impact Strength, Izod test	D 256	0.2–0.4
Heat distortion temperature, °F	D 648	140–400
Rockwell hardness	D 785	M70–115
Specific gravity	D 792	1.10–1.46
Refractive index	D 542	1.523–1.57
Thermal expansion, 10^{-5}/°C	D 696	5.5–10
Resistance to heat, °F (continuous)		250

The significant properties of polyester resins depend on the application or use of the cured system. These properties fall into the following categories: physical properties (mechanical properties and physical constants), electrical properties, chemical resistance, and weathering characteristics. Many parameters change these properties such as temperature, aging, compounding, curing, and other variables. Accordingly, users of polyester resins in filament-wound fabrication evaluate the resins under actual conditions of fabrication and use.

A typical listing of the physical properties of cured resins (11) is presented in Table 4.3.

Very little design use can be made of properties of cast resins, for most resin systems contain fillers that modify most of these properties. Correlation can sometimes be developed between the cast and the filled resin, and data presented in Table 4.3 and in other sources (12) are extremely helpful for characterizing the resin system for application.

PHENOLIC RESINS

Phenolic resins are made by condensation of phenols (such as hydroxy benzenes, cresoles, resorcinols, etc.) with aldehydes (such as formaldehyde, furfural, etc.). Although many combinations are possible for resin formation, the basic phenolic resins are combinations of phenol and formaldehyde. These resins are quite common thermosetting materials. Most are dark in color; they have good chemical

resistance, good electrical properties, and very good mechanical strengths. Their heat resistance against deformation is excellent compared to other resins.

During cure, the resin passes through three stages: A-stage or resol stage, B-stage or resitol stage, and C-stage or resite stage, which is the final cure of a phenolic part. The phenolic resins can be modified by the addition of plasticizers, pigments, lubricants and fillers during

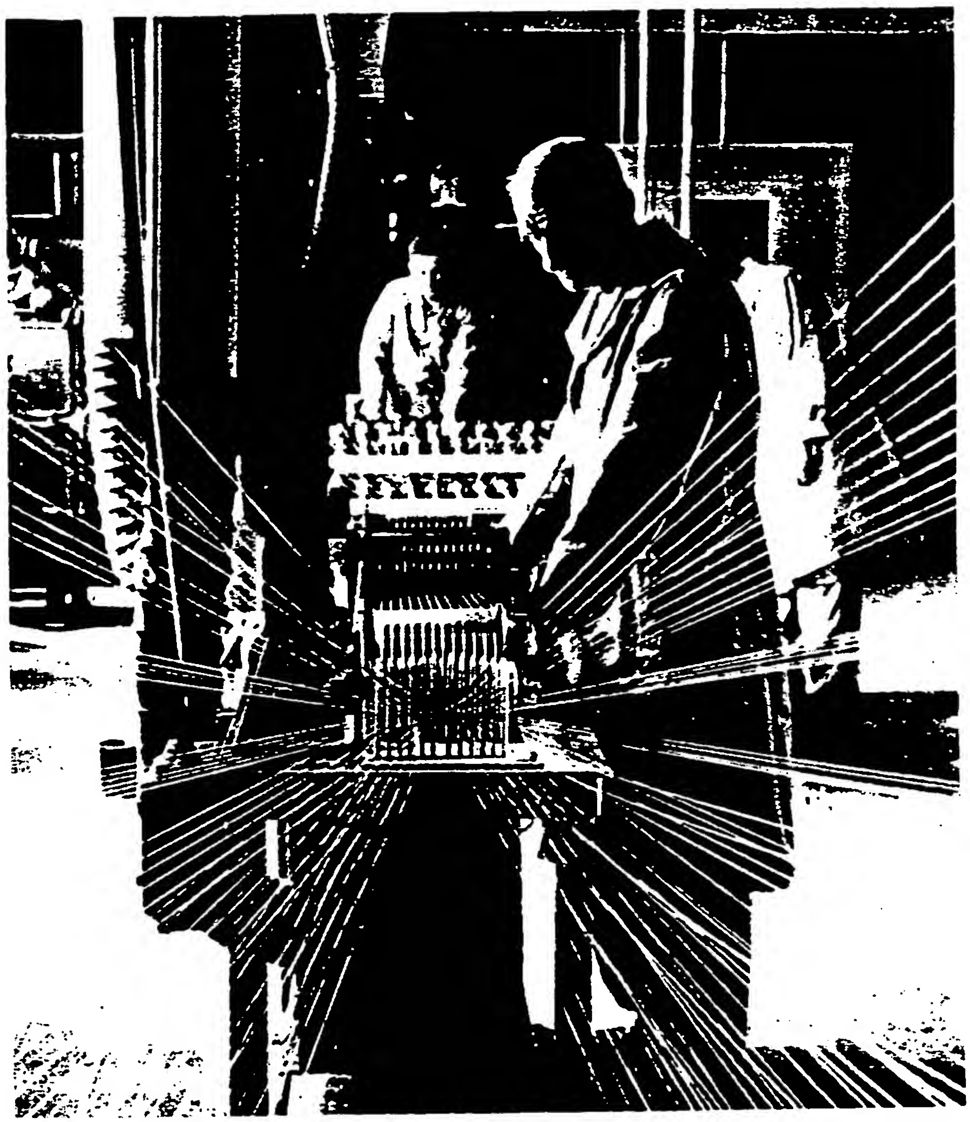


Figure 4.3 Glass filaments traveling from a creel, through resin and to winding machine. (Courtesy of Olin Mathieson Chemical Corp.)

the A-stage. They are very likely the most versatile of the plastics in general use today, and they have wide application.

Phenolics have been widely studied. Recently, efforts have been made specifically to increase their high temperature properties (6). Various unmodified phenolic resins in laminates have been reported to withstand 500°F temperatures for 100 hours and 4500°F for shorter periods. Available laminates in commercial applications have demonstrated flexural strengths of over 50,000 psi and flexural moduli of elasticity of 5 to 6 $\times$ 10^6 psi. About 50 per cent of the flexural strength is reported to be retained after 5 hours at 700°F.

Phenolics are playing an increasingly important role in fiber glass reinforced plastics. Techniques are being developed for their increased application because of their low cost, their high-strength water and chemical resistance, their usually good heat resistance, and their adaptability to preloaded molding techniques (13). Some general properties of molded phenolics are presented in Table 4.4 (14).

The specific characteristics which make phenolic resins interesting for filament winding are long-time heat resistance up to 600°F, short-time heat resistance up to 6000°F, abundance, and low cost. Successful development applications for this type of resin system have involved the use of phenolic prepreg rovings or yarn. By this method, the resin is used in resitol stage condition so that no water condensation occurs during curing. In addition to using leached glass fiber to

Table 4.4 General Properties of Phenolics with Wood Flour and Cotton Flock Filler

Specific gravity	1.32–1.45
Tensile strength, psi	6,500–8,500
Compressive strength, psi	27,000–36,000
Elongation, per cent	0.4–0.8
Flexural strength, psi	8,500–12,000
Import strength, Izod	0.24–0.60
Thermal expansion, linear, 10^{-5}/°C	3.0–4.5
Heat resistance, °F continuous	300–350
Heat distortion, °F	260–340
Water absorption, per cent, 24 hours, $\frac{1}{8}$ inch	0.3–1.0
Resistance to strong acids	fair
Resistance to strong alkalies	poor
Resistance to weak acids	good
Resistance to weak alkalies	good

develop high-temperature filament-wound structures, studies have included the use of asbestos fibers.

SILICONE RESINS

Silicones may be defined as synthetic compounds containing the elements silicon and oxygen and other organic groups; the silicon is present in amounts which substantially affect the properties of the product. While in typical organic carbon compounds, the carbon atoms are attached to other carbon atoms in a repeating pattern, the silicon atom in silicones is cross-linked to an oxygen atom in an alternating pattern of silicon-oxygen-silicon-oxygen atoms. This complex molecular system provides extreme resistance to low and high temperatures, resistance to weathering and oxidation, good electrical and dielectric properties, excellent water resistance, outstanding adhesive resistance, arc and tracking resistance, and good heat-transfer properties (14). Many uses have been developed for the versatile silicones.

The ability of silicone resins to maintain their excellent electrical-resistance properties at temperatures up to 500°F make them ideal for laminates in radomes and high-temperature motors. Silicone resins do not give off toxic fumes in high temperatures, which make them ideally suitable for high-temperature missile and aircraft applications. These silicons have one marked disadvantage, that is, their mechanical strength characteristics of laminates do not equal those of organic resins at room temperature. However, at a temperature of 400°F to 500°F, many organic laminates rapidly weaken, while the silicone laminates do not and are operable for prolonged time periods. Another disadvantage is the higher cost of silicones compared to phenolics.

Table 4.5 lists some of the general properties of silicone resins (14).

Table 4.5 General Properties of Silicone Resins

Specific gravity	1.6–1.9
Tensile strength, psi	4,000–5,000
Compressive strength, psi	9,000–15,000
Flexural strength, psi	9,000–14,000
Impact strength, Izod	0.25–6.0
Heat resistance, °F	450–500
Heat distortion, °F	500–900
Water absorption, per cent, 24 hours	0.2–0.5
Chemical resistance	fair to excellent
Dielectric strength, volts per mil	125–300
Dielectric constant, 10^6 cycles per second	4.1–5.3

Although the silicone resins have excellent properties, they have received limited use in filament-wound applications since they produce low-strength properties at room temperature.

POLYBENZIMIDAZOLE RESINS

The polybenzimidazoles family of polymers is a recent development and breakthrough for high-temperature reinforced plastics and adhesives. It represents a new class of resins, similar to epoxies, phenolics, and polyesters. This class of polymers include many different formulations and modifications. It is essentially a new building block from which many new materials of construction can be developed (15). Research and developments are presently in process to make them applicable in filament winding.

PBI is the term used to identify these materials. These polymers are not dependent upon cross-linking to achieve useful physical properties at temperatures between 700°F and 1000°F. Despite the linear nature of the molecules, thermoplasticity is only a minor problem because of the high glass-transition temperature (16).

When the resin is used with E-glass woven fabric style 181, properties obtained include: ultimate flexural strength of 70,000 psi from minus 100°F to plus 700°F (tested after three-hour soak), flexural modulus of 3.5×10^6 psi for similar conditions, compressive strength goes from 55,000 psi at this low temperature to 40,000 psi at the high-temperature end of these conditions, compressive modulus is 3.5×10^6 psi for similar conditions, flexural strength of 20,000 psi at 1000°F (two-minute soak), and flexural modulus of 1×10^6 psi at 1000°F. These laminates were press-cured at 500 psi and 700°F with postcure of 600°F to 800°F in a nitrogen atmosphere or vacuum. Dielectric constant and loss tangent electrical properties are comparable to epoxy-gloss laminates at room temperature. With epoxy and other conventional resin systems, these electrical properties deteriorate before reaching a temperature of 400°F. With PBI system electrical properties remain the same to at least 1200°F. When using the improved fibers such as "S" glass, proportionately higher properties are obtained.

OTHER RESINOUS MATRICES

Many other resins are mixed, and modified resin systems have been considered for filament winding. Of these, polyurethane or polyurethane-epoxy resins are being evaluated for use in filament-wound structures. These resins are reported to develop increased bond

strength to the reinforcement, greater toughness, with no loss in the conventional strength properties.

Exploratory research to obtain higher heat-resistant resins has involved formulations of polyisocyanurate resins and polymetric metal chelates. Progress to date indicates that thermal stability to temperatures of 700°F is attainable. Further work may result in a resin system having long time thermal stability at temperatures up to 1000°F (15, 16).

OTHER MATRICES

The properties of organic matrix materials are definitely limited by their temperature capabilities. Developments are being conducted on inorganic matrix materials and polyaromatic resin systems. These matrices can provide high-strength composites utilizing available reinforcements which satisfy long-time temperature capabilities at 1000 to 2000°F (17).

Phosphate bonded oxides can develop high plastics deformation under load as compared to conventional ceramic materials. They are chemically and physically stable at 2200°F. Developments with this inorganic matrix involves formulating reinforcement-binder composites which are chemically, thermally, and structurally compatible.

With developments continuing at a rapid rate in order to produce more efficient filament-wound structures at high temperatures, various investigators have been studying the potentials of ceramic matrices (18). Successful structural use of materials such as steel and aluminum is made possible by the ductility which such materials possess. Without ductility, any stress-concentration points cause failure at lower nominal values of tensile stress. Such behavior is characteristic of brittle materials.

Ceramic materials have remarkable high-temperature properties and are usually very strong (19). However, they are brittle and have relatively no ductility. Various methods of overcoming these deficiencies are being evaluated. One basic approach has been the development of ceramic-metal mixes, which are generally referred to as cermets. Another approach, which is of direct interest to the filament-winding industry, has been to incorporate within the ceramic tensile prestressed wires.

Modifications of ceramic bodies have been made in the field of metal-to-metal bonding (20). Ceramic adhesives ranging in thickness from 5 to 15 mils have been developed specifically for producing high-tensile–shear-strength loads. The metal adhesive-bonded sec-

tions can be subjected to temperatures ranging from 1000 to 2000°F.

Aluminum phosphate ceramic matrix systems used in conjunction with silica filament reinforcements have shown good physical and electrical properties at temperatures up to 1000°F. The preliminary physical strength characteristics have been based on flexural tests. Room temperature strength ranges from 10,000 to 15,000 psi. There is relatively no change in strength at the elevated temperatures when tested at elevated temperatures (one-half hour soak at same temperature before testing at the elevated temperature). When six-hour high-temperature soak periods were used, the strength reached 20,000 psi at the same temperature.

SURFACE TREATMENT OF REINFORCEMENT FOR BONDING

Fibrous glass is the major type of reinforcement used in filament winding processes. Glass does not bond well with most resins, however. Consequently, its surface must be prepared for proper bonding with the resinous matrix, in the same manner in which metals need to be primed before a paint is applied.

Glass filaments tend to abrade one another; therefore a lubricant must be added immediately after pulling from the forming orifices. The individual filaments in a bundle do not cling together, so a binding material must be added. Finally, because the resin does not bond to the glass, a coupling agent must be used. Thus the surface treatment must serve three purposes: lubricate, adhere, and couple. Since the lubricating and adhering material interferes with the effective interfacial bonding of the resin to the glass, it must be removed. This process is usually done by "heat-cleaning" or burning-off the original sizing material. After the sizing is removed, a coupling agent, known as a finish, must be applied. Table 4.6 lists some general finishes in current use (11).

Much research has been carried out to determine the nature of the resin-glass interfacial bond and to arrive at a theoretical understanding of its physical and mechanical significance. Even though these studies have been rewarding and have given good results, a complete interpretation of the interfacial reactions is difficult. It is sufficient to say that selecting the proper finish is still an art, and the mechanism by which the finish improves the glass-resin bond is not clearly understood.

To gain optimum strengths in the filament-wound structures the finish must provide good interlaminar resin-glass bonding (1). The answer to the question is still theoretical. Four possible mechanisms

Table 4.6 General Finishes for Fibrous Glass

Finish	Used With	Typ
111	Melamine	Partly desized
112	Silicones	Heat cleaned, fully desized
114	Polyester	Chrome complex
Volon-A	Polyester	Chrome complex
136	Polyester and Silicones	Silane
Y-1100	Epoxies and Phenolics	—
NOL-24	General Purpose	—
A-172	Polyester	Silicone
301	Polyesters, modified	—
T-31	General Purpose	—

have been suggested: The finish provides a molecular link between the glass and resin by primary chemical bonds; it acts as a deformable layer to reduce and relax shear stresses at the glass-resin interface; it increases coefficients of friction between the resin and glass surface; or it provides a combination effect of these three.

The chemistry of the use of finishes is also complex. Most of the studies have been conducted on finishes for E-glass; it is probable that with the advent of the new high-modulus glasses and silica glass, new finishes will have to be developed to obtain optimum properties from filament-wound items using these reinforcements (10).

Two basic finishes have provided the best bonds and have become widely used in the industry. (1) Chrome finishes, such as Volan A, are broadly accepted for polyester and epoxy systems. These are methacrylate chromic chloride complexes, neutralized with ammonia. (2) Silane finishes, such as NOL 24 and A-1100, are universally used to provide good general bonding with polyesters, epoxies, phenolics, and silicones. NOL 25 is the reaction product of allyltrichlorosilane and resorcinol. A-1100 is the hydrolysis product of α-aminopropyltriethoxysilane.

Studies for development of analytical methods and for preparation of new finishes are underway. Of special interest for analysis is an electron microscopy replica technique, which allows the actual surface and configuration of the finishes to be seen. A new but promising approach has been the addition of a finish to the resin during impregnation. The additive used at present is a vinyltriethoxysilane (VTES) (10).

IMPREGNATION OF REINFORCEMENT BY MATRIX

Basic filament reinforcement is essentially continuous and is drawn from a spool for pretreating before winding around a mandrel. Two basic methods for pretreating or impregnating the filament with resin are used. The first basic method, commonly referred to as "wet" system, involves the impregnation of the filaments with liquid resin prior to winding around the mandrel. A second method uses pre-impregnated (wet or dry) filaments which have been wetted and dried with partially cured resin (21).

One of the earliest so-called wet systems was to wind the glass filaments dry onto the mandrel and then impregnate it on the mandrel. Impregnation was performed by applying resin directly on the mandrel as it rotated or taking the wrapped resin-dried mandrel and putting it in chambers. Vacuum, autoclave, and dip tank chambers were used to apply the resin. This method was abandoned by most fabricators very early (22). This method did not permit reproducibility or sufficiently satisfactory properties in applications where efficient structures were being fabricated. However, it is still used to develop special handling or property characteristics, such as the construction of gun barrels, by filament winding. In the past the wet system was used almost exclusively. At present the major usage is the preimpregnated system. The trend for the future is that the preimpregnated system will be used exclusively as major production programs are developed.

As the term implies, the wet method applies a liquid resin to the filament before winding, while still wet, around the mandrel. Selection of the resin is limited to resins which are adaptable to liquid application, that is, epoxies and polyesters. The most persistent objection to the use of a directly applied liquid resin is that it is not tidy. The working area around the winding machine becomes liberally coated with several layers of accidental drips of various resins. Because the machine structure is usually painted, it is impractical to remove the drippings with solvent because this also removes the paint.

Another disadvantage of this method is the low rate of speed at which the filaments can be impregnated with liquid resin. If a filament is drawn through the resin bath too rapidly, little if any resin will cling to its surface. Since the filaments may not be wound around the mandrel any faster than they can be thoroughly penetrated by the resin, the winding process is slow. One way to shorten the "wetting" time is to pass the filaments between two very soft resin-impregnated rubber sponges after they emerge from the resin bath. The soft

"stroking" of the filaments by the sponges tends to force resin between adjacent fibers and distribute the liquid uniformly through a band of parallel fibers. It is apparent that resin viscosity plays an important role in the wetting speed of the filament. The more viscous the resin, the slower the process.

In this method large quantities of resins are usually wasted either by being left in the tank at the end of a run or by being scrapped off the part itself. In addition, it is impossible to be sure that the resin content of the part will be accurately reproduced from part to part. A further disadvantage is the fact that the resin content increases with larger-diameter parts when constant winding tension is used. This increase in resin content is very undesirable when high-strength to weight ratio parts are required. In order to reduce the resin content, the winding tension must be increased. This can only be accomplished within defined limits because of the danger of breaking the filaments.

A further problem with wet winding lies in inability to use a large number of resin systems because of the high viscosity. In some cases, high-viscosity systems can be used if they are heated to reduce the viscosity, but this also reduces the pot life and requires additional equipment. Still other systems cannot be used even when heated, but can only be used by thinning with solvents. Solvent systems, however, cannot be used in wet filament winding, since there is no practical way to remove the solvent before the filaments are applied to the mandrel.

The biggest advantage of the wet system is economy. An epoxy-E-glass system averages about 92 cents per pound for applications to military specifications and 57–60 cents per pound for commercial products. This is compared with a cost of $1.45 per pound for a preimpregnated system of the same resin and glass. Technically, a wet system provides a less permeable vessel, since the excess liquid forces entrapped air bubbles to the surfaces. This is accomplished by simple bubble-exudation and by the pulsing-squeezing action as each additional taut filament is laid onto the surface.

For a compound-curvature surface, an even-coverage pattern produces an open "net" structure. Previously, it was believed that the resulting interstices should be filled or "potted" with resin to distribute stress and prevent chain-reaction ripping at failure. This philosophy is currently open to question. If these interstices need not be filled, it is then possible to remove all excess resin, for example, by centrifugal spinning.

Although it is believed that a wet system provides better impregnation of the reinforcing fibers compared to a solvent-assisted pre-

impregnation, either will be affected by the care and consistency of the operation. The physical geometry of the impregnated fibers is easier to predict and control in a wet system. The optimum configuration of the strand at the point of winding is a flat band of parallel fibers.

In a wet system, this is accomplished by drawing the band of filaments over a rounded surface, the "eye," immediately before contact with the mandrel. This causes the filaments to rearrange themselves to assume uniform tension and splay into a flat ribbon as they pass over the curved surface. Redesign of the "eye," from a cylindrical to a slightly crowned surface, allows precise rearrangement of parallel fibers into a flat band which approaches a theoretical optimum. This is best accomplished with a wet system, since a liquid will not interfere with the rearrangement of the fibers and, in fact, provides the necessary lubrication to facilitate the adjustment and prevent fiber damage.

Preimpregnated wet system is a modified system, which is more efficient than winding immediately after the resin bath. It has been in use for the shortest period of time in the field of filament wrapping. Here the filaments are preimpregnated with resin and partially cured before being used for winding. This method of impregnation has been widely used for other reinforced plastic work.

Several important advantages follow. A higher production rate is available. Because the resin is preapplied to the filament elements, winding speed is not limited to the speed of adequate wetting and therefore may be increased to the physical limits of the winding machinery. Easier impregnation techniques are used. A rig to unwind, impregnate, and rewind the filaments which optimizes the impregnating operation can be assembled. Thus it is possible to treat the filaments with care and to minimize handling damage. The rig can be a simple installation requiring very little surveillance; therefore, the operation will be unhurried. The liquid resin can be treated as necessary to provide better wetting, including heating it to reduce viscosity or to "hot melt" a normally solid resin, agitating it to maintain a balanced compound, etc. None of these features can be economically included in a winding machine. Better impregnation is developed. After "wet-impregnation," a spool of impregnated filaments must be protected from heat, to avoid advancing the cure or increasing viscosity, until the winding operation. This is accomplished by placing the wet-impregnated spool in a plastic bag and storing in a cool refrigerator. During the hours of storage the resin migrates throughout the mass, seeking a natural balance and infiltrating areas that were

not reached during impregnation. Air that has been entrapped deep in the filament cord is displaced by infiltrating resin. A vacuum tube may be inserted in the storage bag to assist in removing air or volatiles. Control of resin content is easily accomplished. The amount of resin picked up in the "wet" system is difficult, if not impossible, to control. It is obvious that a bench-top impregnating device provides a better opportunity for control of net resin percentage. Before and after weighing is usually sufficient, assuming that the job of "in-line" impregnation has been reasonably consistent. Of even greater significance, the "wet-spool" weights afford an accurate prediction of the weight of impregnated material used in a winding operation. The ability to better control and predict the resin-to-glass ratio minimizes the possibility of overweight rejects. A hidden advantage of using preimpregnated roving for winding lies in the fact that a greater variety of shapes can be wound. Because of the possible high tack of the material, the roving will not slide off of steep slopes as will roving that is used in the wet stage. To a great extent, the use of preimpregnated material also reduces the dermatitis problem to a minimum.

For the small shop, preimpregnated materials eliminate the need for resin handling and chemistry knowledge. It also reduces the amount of materials that must be inventoried. In addition, all the research and test facilities of the raw material suppliers are available. There is no waste material and small runs of one or two items can be made with a minimum of time and effort. Some of its prime advantages lie in its ability to overcome the disadvantages of wet winding. Being able to use all resin systems is extremely important. It may be this factor alone that dictates the use of preimpregnated materials.

The preimpregnated dry system is suitable for a number of resins which do not readily lend themselves to direct application in liquid form. These are the resins which are normally solid or thick, and which require the addition of a diluent to thin them for practical use. The removal of these diluents requires gentle heat and large volumes of dry air, which cannot easily be included in the winding operation, but which can be accomplished when preimpregnating the filaments in a tower operation. This preimpregnated or "dry" system can be used with resins which are essentially the same (or very similar to) as those resins commonly referred to as "wet" resins. However, since these are deviations from the normal, consideration is given here only to resins that cannot be used in a wet system. These can be

classified as phenolics, phenyl silanes, silicones, diallylphthalates, and isophthalates.

In addition to the higher cost of the impregnated supply stock, the preimpregnated dry system requires more expensive tooling and winding machinery. For example, to afford a degree of plasticity to the resin sheath the filament should be heated between the supply spool and workpiece. This allows the filament to push most of the resin to one side and contact the underlying filaments upon tangential contact with the workpiece. In addition, the mandrel should be heated or warmed throughout the winding operation to further assure wetting of the applied filament by the resin matrix through gentle migration of the softened resin into areas immediately adjacent. Some air will be removed in this manner, but the end product will always be essentially porous and will exhibit a tendency to "weep" under internal hydrostatic pressure.

An annoying characteristic, if not an actual disadvantage, of preimpregnated dry system filaments is the method of packaging. As the filament is wound on a spool after impregnation, the ribbon is bent in an arc parallel to its flat plane at both ends of the spool each time it reaches an end and reverses direction to start another layer. As this resin-impregnated ribbon is subsequently drawn from the spool for the winding operation, it is dry and usually quite stiff prior to entering the filament-heating zone. The "kinks" caused by the bending cannot be straightened out without placing too great a tensile strain on the filament; therefore, all fairways and pulleys between the supply spool and the heating zone are subjected to erratic jerking and whipping as the "kinks" pass over and through them. This also causes the stiff resin to crack and craze on the inner radius of the bend line.

Primary advantage in the use of a "dry" or "wet" preimpregnated system is not related to physical performance, but to the rate of application, which is limited only by the performance of machinery at reasonable velocities. An incipient limitation exists within the preheater because the radiant heat must be very high to achieve sufficient heating of a filament passing through this zone at high speed. It is recommended that some device be employed which will automatically shut off the heating elements if the filaments should break (a simple "electric eye" connected to a magnetic relay), or if the filament velocity varies by more than about 5 per cent to 7 per cent. It is necessary that the operator control and monitor this filament heating at all times. Because it is advantageous to keep the winding mandrel warm during winding, as explained, it is possible to cure the work in place by increasing this heat. This is usually accomplished by leaving

the workpiece in the winding machine and placing a heat-retaining insulating shroud around it. This method also makes it possible to rotate the workpiece during cure. Other advantages are apparent, such as the possibility of using resin systems which are not amenable to simple dipping, elimination of the dripping of a "wet" system, and so on.

It is always necessary to brake or slow down the filaments during winding to achieve the desired tension. It is believed that this tension should be as high as possible. It is usually achieved by determining the maximum breaking strength of the filament and releasing the back tension just enough to reduce occasional breaks to a practical minimum. This tension is varied as wall thickness increases. In general, a wet system will not stand as much back-tension as a dry system because the wet resin does not transfer shear and each filament is without assistance from its neighbors. To prevent overrunning and "back-lash," slight braking to the supply spool is employed. Progressively more tension along the treatment line is added until adequate tension is obtained between "eye" and workpiece.

In the dry system it will be possible to achieve very high back tension. First, because the individual fibers and their neighboring ends are stuck together and resist breaking by acting in unison in resisting tensile forces. Second, it is necessary to use a higher braking force since a portion is absorbed in compacting the fibers on the mandrel.

Unlike a "wet" system in which back tension is accomplished preferably in progressive increments along the line, a "dry" system achieves all the required braking action at the spool. Because of the hard, slightly tacky surface usually characteristic of preimpregnated filaments, it is generally impractical to use tensioning "combs" or wrap-around drag bollards because of resin pick-up and stripping. "Eye" design is a problem arising from the need to decide whether to use a revolving pulley or a bar. The pulley becomes loaded with resin quite rapidly because it is the last point in the system, immediately down-stream from the preheating zone, and carries filaments that are sticky with hot resin. A bar tends to strip resin and pile it up. Where possible, the heating zone should be located after the "eye" in the stretch between "eye" and workpiece surface which will avoid this problem.

The packaging of either wet or preimpregnated materials is important to standardize the equipment required by the fabricator and to develop the most efficient structures. Standardization of the package as related to equipment requirements includes core size, weight of package, length of package, and number of ends.

Packaging characteristics which have a marked effect on the properties of the final part involve the technique in winding reinforcement, use of inside or outside pull-out mechanism, and use of separator layers (if required to prevent locking of the preimpregnated materials). In order to obtain good parts, only outside pull-out techniques should be used to avoid twists in the material while winding. The material should be wound on the core in a uniform helical pattern with a relatively high angle to the axis of the core. The helical pattern prevents the material from cutting down into lower layers and shredding as it is being unwound. The high angle also prevents shredding, since very little dragging across the spool occurs during unwinding.

Preimpregnated materials with high tack require a separating strip. In the case of preimpregnated materials, standards are now being developed by the American Society of Testing Materials and Society of Plastics Industry on shelf life, resin content, tack, and per cent flow. Although the shelf life will be determined usually by the resin system, the resin content, tack, and per cent flow depend on the part being wound. Generally, high-strength parts require low resin contents, about 10 per cent by weight. This in turn also limits the amount of flow possible. High tack is usually required only on parts that are difficult to wind.

SUMMARY

There are many complete reference books, which describe various resin systems, their properties, and their applications. Some of these are listed in Table 4.7 for use by anyone who desires to delve more deeply into the diverse aspects of the problems of resinous matrices.

The present situation with respect to the resins can be summarized generally as follows (10). Epoxies will continue to dominate the filament-winding fabricating effort, although silicones, phenolics, and phenyl silanes will find special uses in high-temperature applications. Some of the newer higher-temperature modified polyesters will also enter into certain high-temperature applications, while the general purpose polyesters will continue to be used in many structural elements. A large number of available systems of epoxies are in development and will become important matrix materials. Among these, which must be considered, are the epoxidized novalacs, the peracetic type of epoxides, the aliphatic and aromatic polyepoxide types, and the straight chair aliphatic epoxy type.

It is not likely that a universal resinous matrix will be found for all filament winding. Such a system is not practical or desirable. It

Tabl 4.7 Titles f R ferenc Books

Subj ct	Author
1. Technical Data on Plastics	MCA, Inc. (23)
2. Source Book of the New Plastics, Volumes 1 and 2	Simonds (24)
3. Polymers and Resins	Golding (25)
4. Fiberglass Reinforced Plastics	Sonneborn, Dietz, and Heyser (13)
5. Glass Fiber Reinforced Plastics	de Dani (26)
6. Laminated Plastics	Duffin and Nerzig (14)
7. High-Temperature Plastics	Brenner, Lun and Riley (6)
8. Modern Materials	Hauser (27)
9. Properties and Structure of Polymers	Tobolsky (28)
10. Mechanical Properties of Polymers	Nielsen (29)
11. Processing of Thermoplastic Materials	Bernhardt (30)
12. Epoxy Resins	Lee and Neville (4)
13. Polyester Handbook	Scott Bader (12)
14. Polyester Resins	Lawrence (11)
15. Silicones	Meak and Lewis (31)
16. Silicones and Their Uses	McGregor (32)
17. Phenolic Resins	Gould (33)
18. Acrylic Resins	Horn (34)
19. Polyamide Resins	Floyd (35)
20. Polyurethanes	Dombrow (36)
21. Concise Guide to Plastics	Simonds (5)
22. Asbestos	Rosato (37)

is expected that the applications will dictate the requirements of the matrix. With a wide choice of materials available, the designer can select the particular matrix which will furnish the important composite properties for the specific structural component.

References

1. Owens-Corning Fiberglas Corporation, *Technical Bulletin*, "Fiberglas Reinforced Plastics" (August 1962).
2. J. J. Madden, SAMPE *Meeting Report*, p. 301 (March 1961).
3. J. V. Kindall and S. E. Susman, SAMPE *Meeting Report*, p. 99 (March 1961).
4. Henry Lee and Kris Neville, *Epoxy Resins*, pp. 3–21, McGraw-Hill Book Company, Inc., New York (1957).
5. H. R. Simonds, *Concise Guide to Plastics*, Reinhold Publishing Corporation, New York (1960).

6. W. Brenner, D. Lum, and M. W. Wiley, *High Temperature Plastics*, Reinhold Publishing Corporation, New York (1962).
7. J. V. Kindall, F. J. Riel, S. E. Susman, and S. Yureuka, WADD Technical Report 60-791, Part I (August 1960).
8. J. V Kindall, and S. E. Susman, "High Temperature Resin System for Glass Filament Wound Composites," ASD Contract No. AF33 (616)-6737, 1961.
9. *Plastics Technology*, p. 14 (April 1963).
10. Plastec Report 10, Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, New Jersey, p. 166 (May 1962).
11. J. R. Lawrence, *Polyester Resins*, p. 39, Reinhold Publishing Corporation, New York (1960).
12. *Polyester Handbook*, p. 100, Scott Bader and Co., Ltd., London (1959).
13. R. H. Sonneborn, A. G. H. Dietz, and A. S. Heyser, *Fiberglas Reinforced Plastics*, pp. 33–34, Reinhold Publishing Corporation, New York, Seventh Printing (1959).
14. D. J. Duffin and C. Nerzig, *Laminated Plastics*, pp. 17–22, Reinhold Publishing Corporation, New York (1958).
15. D. L. Grimes, IAS Paper No. 63-45 (January 1963).
16. H. H. Levine, "Polybenzimidazole Resins for High Temperature Reinforced Plastics and Adhesives," AF ASD Dayton Symposium (December 1962).
17. D. V. Rosato, *Adhesive Age*, **3**, No. 12, 38 (1960).
18. F. J. Koubek, H. A. Perry, and I. Silver, Naval Ordnance Laboratory Report, NAVORD 6056 (February 1958).
19. T. L. Johnston, R. J. Stokes, and C. H. Li, "Fundamental Mechanical Behavior of Composite Crystalline Mixtures," Honeywell Research Center, Hopkins, Minnesota (August 1959).
20. S. Sklarew, "Reinforced Refractory Ceramic Coatings," The Marquardt Corporation, Van Nuys, California (August 1959).
21. E. E. Hardesty, Narmco Research and Development Engineering Report No. 61-E20, San Diego, California (April 1961).
22. N. A. Beaucamp, Narmco Research and Development Engineering Report No. G1-E3 (January 1961).
23. Manufacturing Chemists' Association, Inc., "Technical Data on Plastics," Washington (February 1957).
24. H. R. Simonds, *Source Book of the New Plastics*, Vols. 1 and 2, Reinhold Publishing Corporation, New York (1959 and 1961).
25. B. Golding, *Polymers and Resins—Their Chemistry and Chemical Engineering*, D. Van Nostrand Company, Inc., New York (1959).
26. A. de Dani, *Glass Fibre Reinforced Plastics*, Interscience Publishers, Inc., New York (1960).
27. H. H. Hausner, *Modern Materials*, Vol. 1, Academic Press, Inc., New York (1958).
28. A. V. Tobolsky, *Properties and Structure of Polymers*, John Wiley and Sons, Inc., New York (1960).
29. L. E. Nielsen, *Mechanical Properties of Polymers*, Reinhold Publishing Corporation, New York (1962).
30. E. C. Bernhardt, *Processing of Thermoplastic Materials*, Reinhold Publishing Corporation, New York (1959).
31. R. N. Meak, and F. M. Lewis, *Silicones*, Reinhold Publishing Corporation, New York (1959).

32. R. R. McGregor, *Silicones and Their Uses*, McGraw-Hill Book Company, Inc., New York (1954).
33. D. F. Gould, *Phenolic Resins*, Reinhold Publishing Corporation, New York (1959).
34. M. B. Horn, *Acrylic Resins*, Reinhold Publishing Corporation, New York (1960).
35. D. E. Floyd, *Polyamide Resins*, Reinhold Publishing Corporation, New York (1958).
36. B. A. Dombrow, *Polyurethanes*, Reinhold Publishing Corporation, New York (1957).
37. D. V. Rosato, *Asbestos, Its Industrial Applications*, Reinhold Publishing Corporation, New York (1959).

5 Manufacturing

When reviewing filament-winding manufacturing procedures it is important to recognize the influence they have on the end item. Factors to consider are related to mandrel stiffness and surface finish, winding speed, precure-resin condition, accuracy in filament alignment and tension control, temperature control during and after winding, removal of part from mandrel, nondestructive testing and inspection, retaining manufacturing history, and storage or packaging.

Although the filament-wound motor chamber industry is 15 years old, the main development occurred in the last 4 years with different machines being produced. To date the largest and most structurally efficient case built by an automatically controlled machine resulted in a 156-inch-diameter by 25-feet-long chamber. It was designed to burst at 1350 psi at a cylinder wall stress of 66,000 psi using E-glass (1).

TYPES OF MACHINES

Circular Types

The winding machine consists essentially of a mandrel and a reinforcement feeding head. These components can be made to operate by either simple or relatively complex techniques. One of the more basic techniques simulates the operation of a lathe with the mandrel in the horizontal position. The mandrel rotates, and the feeding head

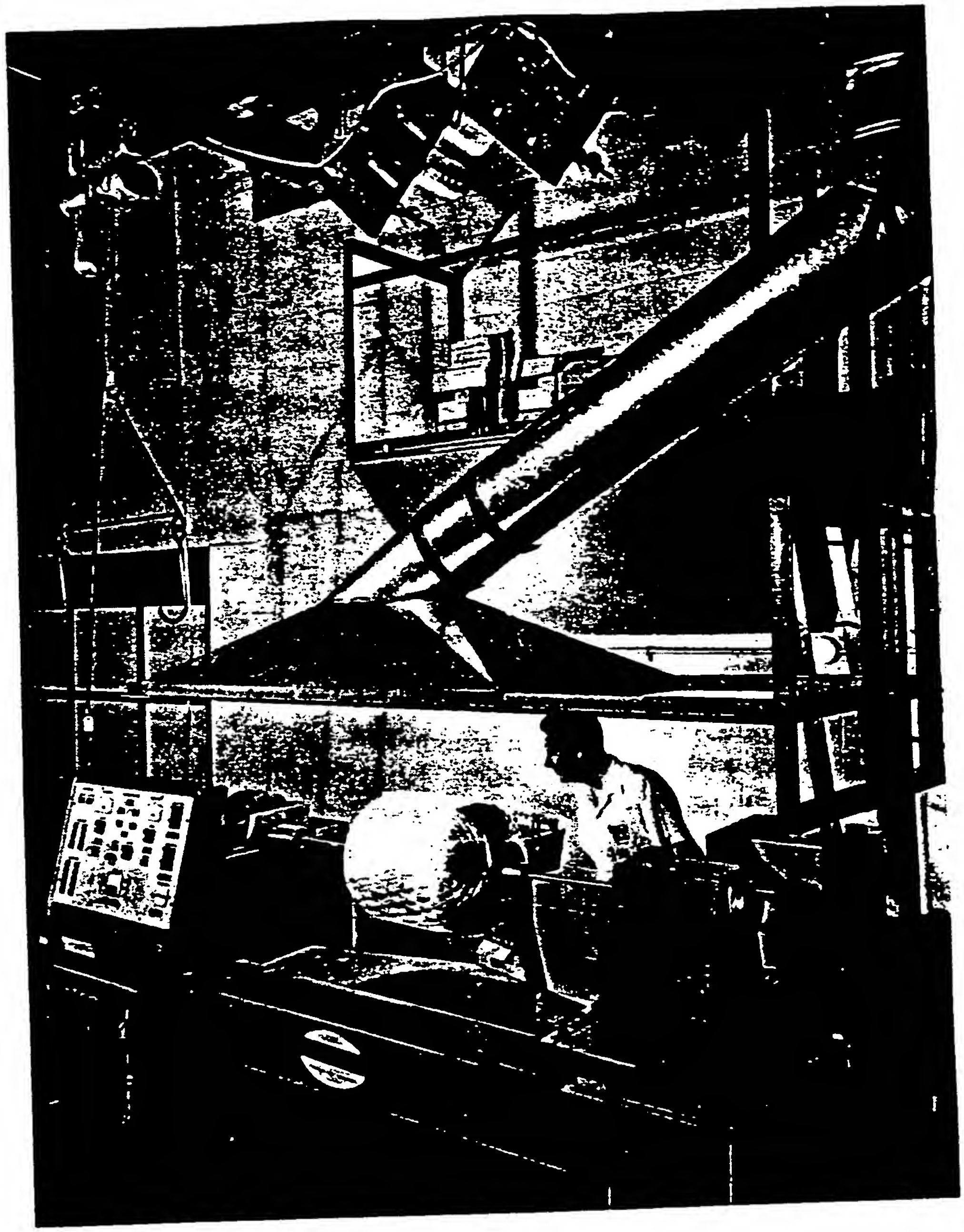


Figure 5.1 Automatic horizontal filament-winding machine; geometric pattern controlled by punch tape data processing techniques. (Courtesy of Thompson Ramo Wooldridge, Inc.)

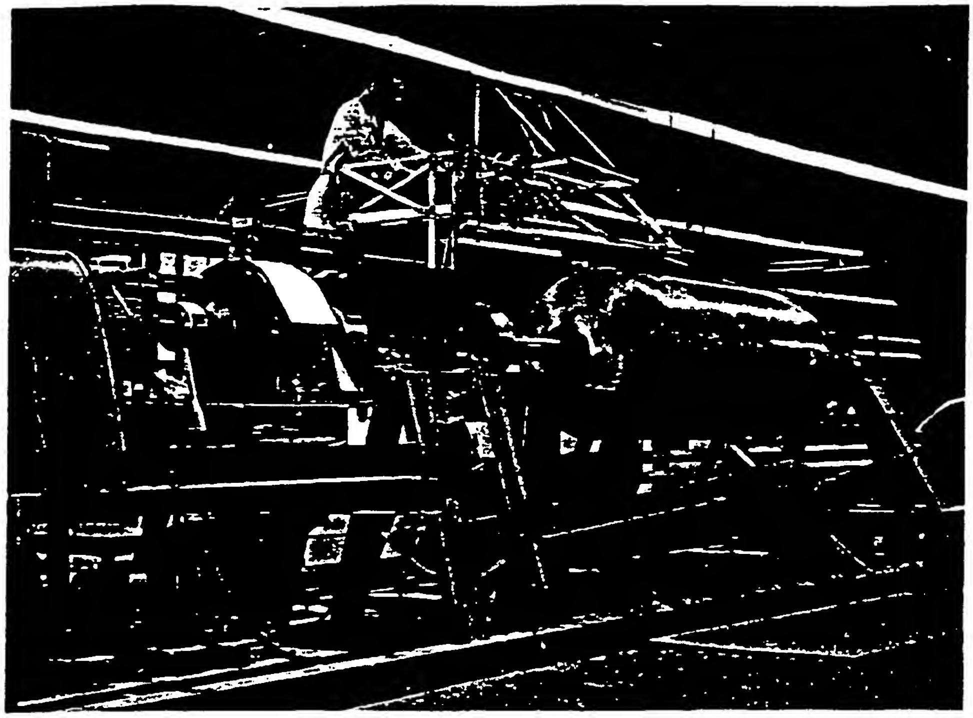


Figure 5.2 Overhead traversing feed head-winding machine; 30-inch-diameter rocket motor being wound. (Courtesy of Lamtex Industries, Inc.)

traverses back and forth along the length of the mandrel. In the lathe-type machine helical winding patterns ranging from 5 to 85 degrees can be accurately positioned. Circumferential windings can be included with the helical windings.

Winding is also accomplished in machines where the axis of the mandrel is in the vertical position. These planetary-type machines generally have the mandrels rotating at very slow speeds. This technique is preferred for the larger mandrels in order to eliminate or reduce its deflection. It also provides for a very uniform fiber speed and easier method to wind around end enclosures. In operation a rotating arm passes over the forward and aft poles of the mandrel while it rotates. For large units, filaments are fed through a series of rollers to produce desired wide tapes in order to lay down more glass during each rotation.

Machines are also being used with mandrels rotating in a tumbling motion. They basically rotate perpendicular to the main longitudinal axis. In relationship to the plane of rotation, its longitudinal axis is offset by an angle equal to the desired helical winding pattern to be

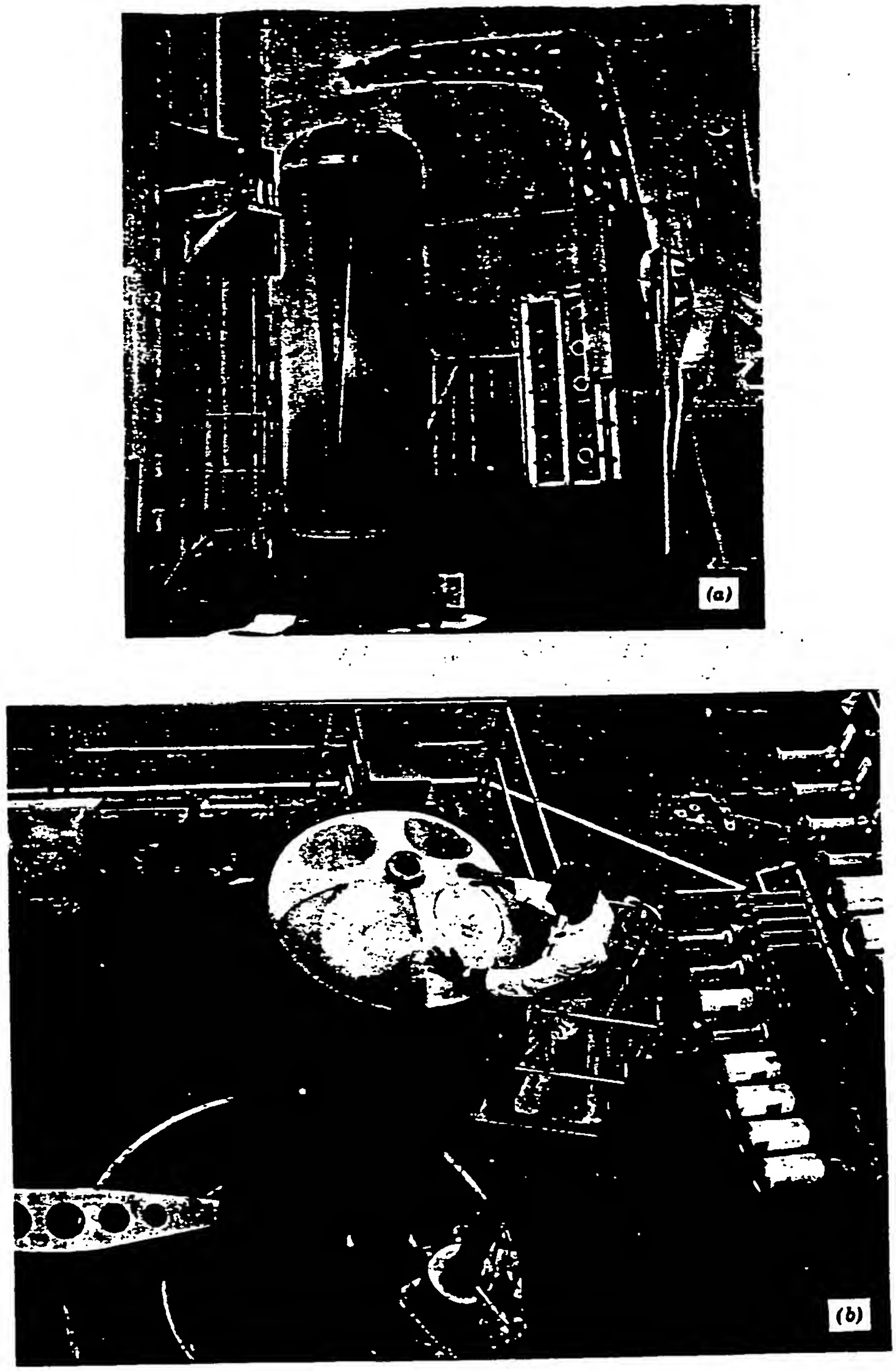


Figure 5.3 Vertical winding machine applying longitudinal glass strands to a solid rocket motor case for Navy's Polaris A-3 first-stage motor. (*a*) Side view, (*b*) end view. The hoop wrap is applied by winding arm on the left of (*a*). (Courtesy of Aerojet-General Corp.)

used. These tumbling-type machines permit filaments to be placed very easily over the complete surface of the mandrel with an overall high accuracy of control.

Another technique employs a rotating mandrel traversing backwards and forwards while the feed head remains stationary. Other complex systems use the feed head moving circumferentially and longitudinally around a mandrel. In this latter case, the mandrel can also be rotating. Electronic data-programing equipment can be used with the winding machines to simplify and properly orient complex operations.

The more elaborate operating techniques permit the glass to be fed directly from the feeding head to the mandrel via a camelback arm. This type of operation reduces the number of turns or bends the fiber encounters prior to being applied directly around the mandrel. Filament can be fed up to at least 500 feet per minute.

The specific method of winding is dictated by the different variables associated with design, mandrel construction, composite materials, and degree of accuracy parameters. More specific controlling factors include weight and sizes, number of parts required, curing facilities, and shape. In regard to shape, most of the development and production units have been concerned solely with components that were surfaces of rotation; for example, spheres and cylinders. Techniques have now been applied to filament-winding boxes.

Filament-wound composite plastics are also being made up specifically to be used as prepregs to fabricate molded parts. The composite material is wound on cylindrical mandrels in predetermined helical layups. The material is slit axially and removed from the mandrel. These flat prepregs can produce exceptionally high-strength end items, because they can contain high glass content as compared to the more conventional woven-glass fabric prepregs.

Rectangular Types

A new versatile machine has been developed to wind rectangular or square corner containers. Figure 5.4 shows a fully automated box winding machine which is wrapping a low-cost commercial 13-quart dairy milk case (2).

The mandrel used is fabricated from aluminum. The boxes are parted around the center after curing. In this application, glass roving is fed from spools arranged radiately around the main drive shaft. Each spool is mounted in an individually tiltable, spring-loaded cradle designed to compensate for tension change as the diameter of a spool

decreases. This action is accomplished by using the resulting change in centrifugal force.

If desired, this machine can rotate the spindle at low speeds so that the operator can visually align the filaments to set a desirable pattern. When the correct pattern is obtained, the operator locks the controls and puts the spindle at production speed.

The major problem in the design of this machine was the fact that when a box is wrapped, all six faces must be covered. This means that there is no place to attach supports to the mandrel and still be able to shift it into all the necessary wrapping of positions. The problem was solved through the use of hydraulic support tables, which sense the box position, shift it about on its axis vertically, and rotate it in a horizontal plane between each wrap cycle. This approach produced

Figure 5.4 Industries first production machine for filament-winding rectangular shapes; fully automated. (Courtesy of Ferro Corp., Goldsworthy Engineering Division.)

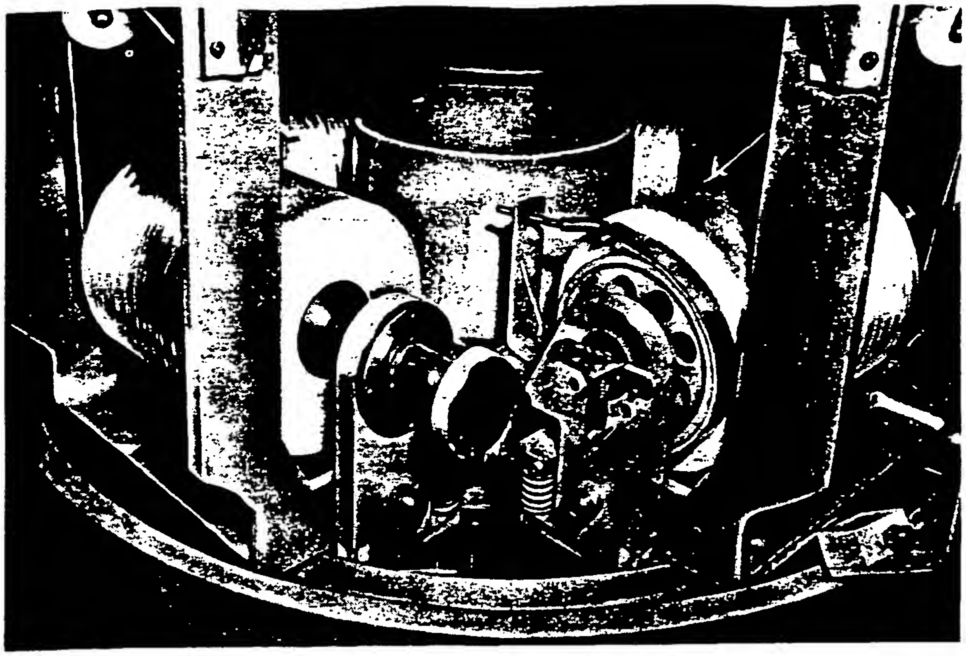


Figure 5.5 Glass roving spools arranged radially around main drive shaft in rectangular winder. (Courtesy of Ferro Corp. and *Reinforced Plastics.*)

a series of design problems caused by the high loads imposed on the mandrel when it is in the long position due to roving tension and acceleration variables. This problem was resolved by means of non-rotating clamp tooling on the tables.

This machine can wrap wet or prepreg materials. Figure 5.6 shows how the position changes are accomplished. For winding position 1, the box is supported at the top and bottom by supports marked 1 and 2. To shift from winding position 1 to winding position 2, the top support 1 is released, an additional support from the left is extended until it reaches the box; then supports 2 and 3 are rotated until the box has shifted 90 degrees. The next cycle involves support 3, which is rotated 90 degrees, and support 1, which is again engaged. The box is then ready for winding in the second plane (winding position 2), and so on.

METHODS OF WINDING

In developing extremely efficient structures, filaments are generally applied to a mandrel by one of two basic methods of winding. These are circumferential winding and helical winding. Circumferential

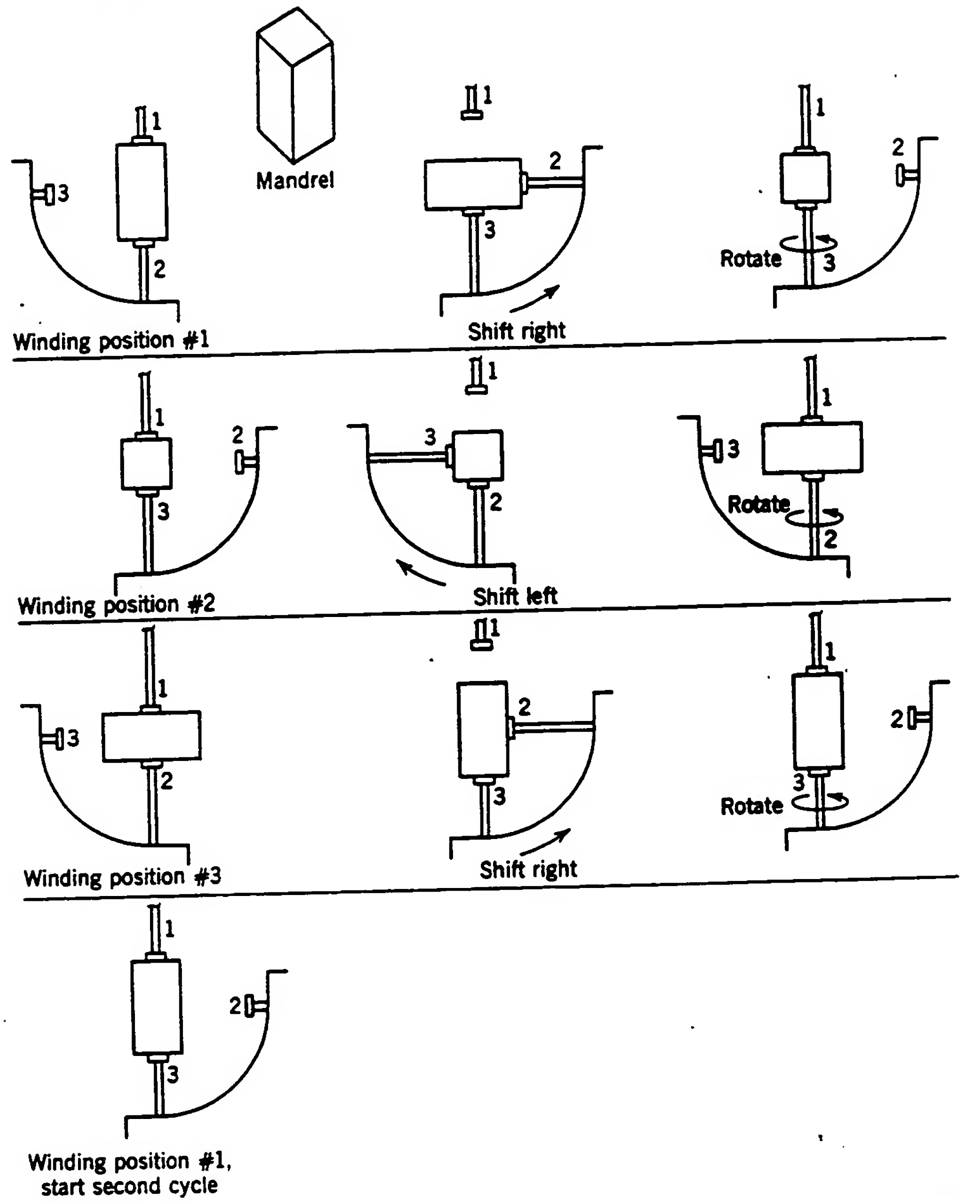


Figure 5.6 Box winding machine: position changes of clamp tooling to wind boxes. (Courtesy of Ferro Corp., Goldsworthy Engineering Division.)

winding does not involve complex techniques. The impregnated reinforcement, in either single or multiple strands, is laid down on a rotating mandrel at approximately a 90° angle with the axis of rotation. The movement of the carriage directing the reinforcement to the mandrel advances the material at a predetermined amount de-

pending on the thickness of wrap desired. For a heavy wrap, the material will overlap the previous material to a greater extent than it does for thin wraps.

Circumferential windings are capable of resisting hoop stresses only. In order to make parts that will also withstand longitudinal loading, it is necessary to place material in the longitudinal direction. In general, longitudinal winding material is laid down by machine operation techniques between layers of circumferential material. With this method of winding, it is not possible to form integral end closures. If closed vessels are to be made, the ends must be fastened to the wound section, either by mechanical means or by adhesive bonding (3). Sometimes, longitudinal material can be extended partially over the ends to help retain them.

Circumferential winding is used when extremely high-quality properties in the hoop direction are required, for example, for binding bands on electric motors. It cannot be used when the part to be wound has slopes of more than 20° when wet roving is used, and more than 30° when preimpregnated roving is used.

For applications where integral ends are required or where angles

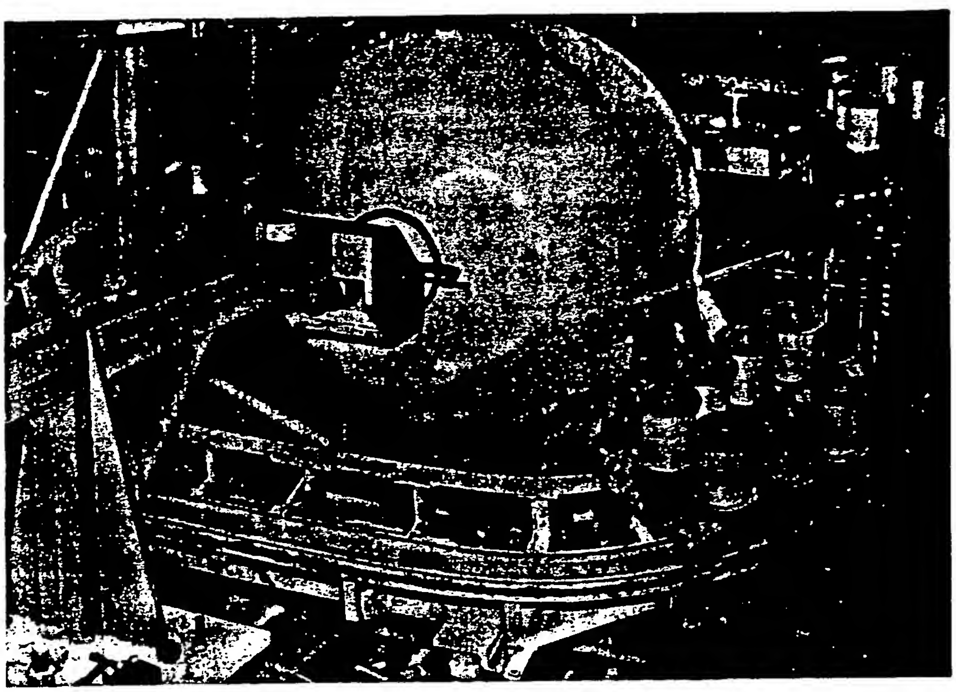


Figure 5.7 "Race track" winder with 60-inch double aft closure mandrel for modular case. (Courtesy of H. I. Thompson Fiber Glass Co.)

of more than 30° are to be wound, the helical method of winding is employed. This method is similar to the circumferential technique, in that the mandrel rotates while an advancing feed places the reinforcement in the proper position. However, the feed advances at a much faster rate. This results in the reinforcements not being laid down at an angle of 90° with the axis of the mandrel.

Depending on the ratio of the mandrel speed to the feed rate, reinforcements are laid down at angles anywhere between 25 and 85 degrees. In helical winding, no longitudinal material need be laid in by hand, since the low angles of possible winding enable reinforcement that can take the longitudinal loads to be laid down. By varying the angle of winding, any ratio of hoop to longitudinal fibers can be obtained.

Helical winding requires very precise control to distribute the material uniformly over the mandrel. The design for this type of a winding machine is much more complex than it is for a circumferential machine. This complexity is further extended when parts with changing cross sections are to be wound. However, only helical winding techniques can be used to produce this kind of parts.

In order to obtain the ultimate strength properties from a filament-wound structure, it is desirable to have all the loads acting along the path of the reinforcement. In some instances, this can be accomplished readily, e.g., in parts in which there are only hoop loads. In other cases, such as in closed pressure vessels, this can be accomplished only by a proper design of the vessel itself. For this reason the majority of wound pressure vessels are designed to have an end shape that is a modified ellipse. This shape not only loads the fibers properly but also can be converged by only one angle of winding rather than the several which are required for a hemispherical end shape.

Other winding techniques are also employed in which the mandrel does not rotate. Systems can be set up whereby the feed moves around the mandrel. Other variations do involve the mandrel rotating perpendicular to the polar axis.

The equipment required for winding will vary in accordance with the lapping pattern requirements. Since 1948, all winding equipment in use has been custom built. M. W. Kellogg Co., New Jersey, and Walter Kidde & Co., New Jersey, are organizations that designed and produced some of the original equipment (4). Basically, the circumferential winding machines can be built with minimum effort, whereas helical machines are more costly and require more technical knowledge. A number of machines specifically built for filament winding are now on the open market. These companies offer both

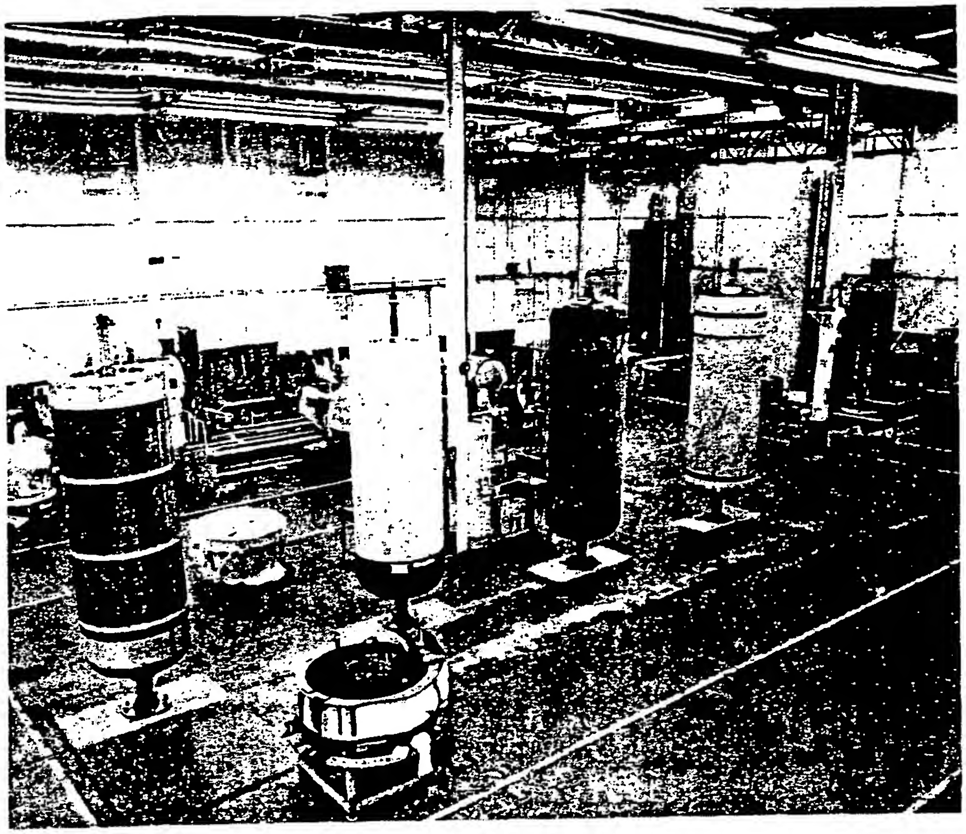


Figure 5.8 A general view of the mandrel assembly area showing (left to right) the segmented aluminum mandrel, mandrel after plastic sweep, mandrel during application of insulation, and mandrel as prepared ready for the filament-winding operation.

From left to right, the view on the far left shows a segmented aluminum barrel-stave mandrel composed of long aluminum barrel segments assembled to a center shaft. Next is an aluminum segmented mandrel, with the plaster over sweep and the forward boss insulation section applied. Next is a completely insulated mandrel composed of the forward insulation section, the aft insulation section, and the cylindrical insulation. The mandrel on the far right has had a final coating applied and is now ready for the filament-winding operation. (Courtesy of Aerojet-General Corporation.)

standard machines and the services to design and build special purpose equipment. These companies include the following:

BMW Manufacturing Company
1740 Abalone Avenue
Torrance, Calif.

Dynetics, Inc.
34 Crestview Road
Mountain Lakes, N.J.

Farrel Corp. (Formerly Farrel-Birmingham)
Ansonia, Conn.

G. Brenner
Newark; Ohio

Larry Ashton
Salt Lake City, Utah

Lou Jansky
Mercury Tool Corporation
Marine Street
Farmingdale, Long Island

McClean-Anderson, Inc.
3461 N. Holton Street
Milwaukee, Wisconsin

Roblex Industries
184 W. Hoffman Avenue
Lindenhurst, Long Island, New York

The Redev Filament Winder
Redev Limited
305 Comstock Road
Scarborough, Ontario, Canada

The second important component required for winding is the winding mandrel. This can vary from a simple bar or tube for making cylinders to an extremely complex collapsible mandrel for making large noncylindrical parts.

Winders are designed so that there is sufficient clearance around the mandrel to develop precision filament orientation. They permit structures to be fabricated by processes in which adequate support is provided for the filament, accurate control is maintained over the winding patterns, and tension-controlling mechanisms are applied. The operating speed and surface temperature of the mandrel is maintained under close controls in order to obtain maximum basic material efficiency.

Multiple filaments (yarn, roving, etc.) can be fed at the same time. These filaments can be drawn from a single or multiple spool. The multiple spool concept can involve locating the spools right next to the mandrel. Since many spools are required, textile creels are principally used. Filaments from the creel are fed through guides or controls in order to develop the proper wrapping pattern.

Another technique, used specifically for fabricating the filament-

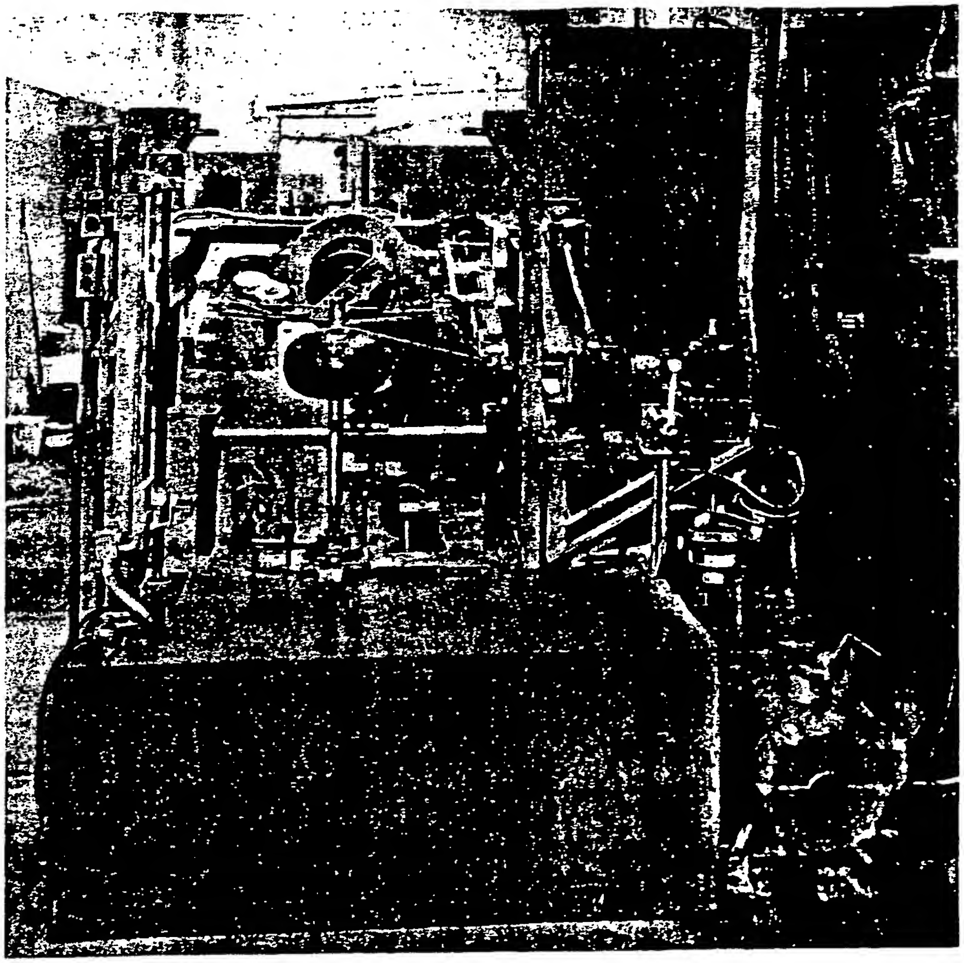


Figure 5.9 Universal winder with pressure vessel. (Courtesy of Brunswick Corp.)

wound pipe, employs a textile braiding machine. The horizontal braided hose technique is most frequently used with an extruded tube or mandrel. Pipe can be made so that the mandrel is removed or becomes an integral part of the structure.

Appendix A lists various filament-winding companies. These companies can produce parts ranging from 3 to 35 feet in diameter and 6 to 90 feet in length, depending on their facilities. Predominantly, equipment ranges in diameter from 5 to 8 feet and in length from 10 to 40 feet. Laboratory filament-winding equipment is also available for research and development. The size of this type of equipment is in the range of 3 feet in diameter by 8 feet in length.

The velocity of the carriage to the rotational speed of the mandrel

is carefully calculated when it is important to fabricate the most precise end item. The carriage is interlocked with the mandrel either mechanically, electrically, or hydraulically to maintain a programmed winding pattern.

Winding equipment contains apparatus to deliver ribbons of rovings or yarns from packages with controlled tension from end to end. The ends are formed into ribbons, which are flat and smooth. A ribbon must be guided around a mandrel in such a manner that it remains uniform regardless of winding pattern geometry. In a wet-winding system it is sometimes very significant whether tension is applied before or after resin impregnation. Some experimenters have reported that at a low winding tension of 2 ounces per glass roving end the cured laminate strengths remain approximately equal. At winding tensions of 8 ounces per end, however, the laminates made only with glass immersed in resin before being tensioned produces equal strength to low winding tension. When tension is applied to dry glass before impregnation loss of at least 50 per cent in strength occurs.

Most wet filament winders use dip tanks. Heated tanks are used with highly viscous systems. Within the tanks, doctor rolls or rods (capstans) can be used to flatten strands and provide lubrication on

Figure 5.10 Glass fiber tube manufacturing equipment using braiding machines. (Courtesy of Lamtex Industries, Inc.)

glass before winding tension is applied. The resin can be forced through the glass strands and air is squeezed out. Squeeze rolls are used after resin dip operations to aid in controlling resin pickup, flatness, and ribbon width.

Effective squeeze rollers are generally made by using one metal (usually polished steel) roller to direct the filament and one rubber faced roller. The rubber permits the use of resins and clean-up solvents. A heavy shaft in ball bearings should be employed because of the high roll pressure needed for proper squeezeout. Raking back the rubber roller can keep the glass from bearing against it, help direct the excess resin back to tank, and prevent loose ends from wrapping around the rubber roller.

Wet ribbon forming can take place outside or inside a resin tank. Different design parameters are used in guiding and forming ribbons. Most ribbon forming takes place in resin tanks. For example, 20-end rovings are guided into a tank with a comb made up of polished steel pins. Hard, smoothly polished material should be used for rollers and guides. Aluminum, steel, Teflon, and nylon produce good rollers. Polished steel is considered best for sliding contact stationary guides.

The handling of prepregs presents many of the same problems as the handling of wet roving or yarn. Spool racks or creels are also mounted on tension devices. The creel must hold spools to allow the filament to whip as it unwinds. Guide eyelits should be on the center line of the spools.

MANDREL

The mandrel can be made of metal, plastic, and/or ceramic. It should be solid, collapsible, or made with a ceramic-type material which, in turn, can easily be removed. The choice of material depends largely on subsequent methods of removing the filament-wound structure. The mandrels require a smooth surface, sufficient strength to permit winding, and adaptability to the type of machine being used. The design of the proper mandrel is not a simple procedure.

The principal materials used to fabricate mandrels are a knockdown or collapsible mandrel, inflatable mandrels, soluble or meltable salts, soluble or meltable plastics, aggregates with soluble or meltable binders, mechanical break-out plasticizers, and combinations of soluble or meltable materials with a collapsible mandrel. The segmented or collapsible mandrels have frequently been used. However, with large-diameter rocket motors, the cost begins to be prohibitive (5). In

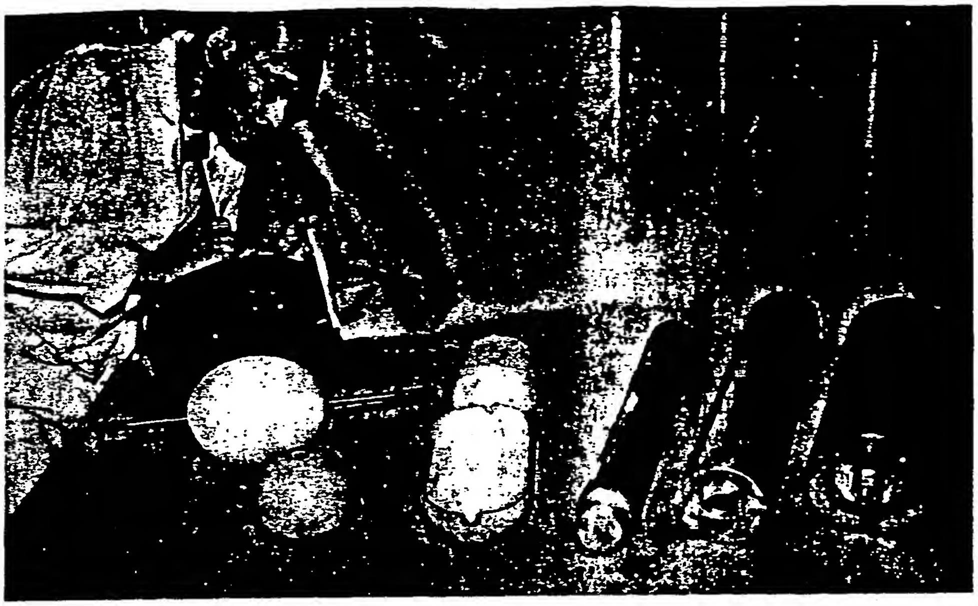


Figure 5.11 Precision small metal and plaster mandrels. (Courtesy of Narmco Research & Development.)

certain applications, the mandrels may cost more than the finished filament-wound vessel. SO WHAT ?(IF YOU MAKE ENOUGH PARTS/MANDREL)

Low-melting alloys which can be used in winding small vessels have not been used to any great extent in the fabrication of large units. This condition is produced by the fact that the high density of the material would result in major technical problems, since a heavier part would be revolving.

Inflatable mandrels have not been too practical because of the difficulty of maintaining close tolerances. They are only used in special applications. Also, in order for them to take any kind of torsional loading, they would require internal support from some type of collapsible spider.

The material most frequently used has been a washout or break-out plaster. This can be used alone in small-diameter structures or in combination with a collapsible support and large-diameter structures.

The residual filament stresses in any filament-wound structure cured on a mandrel depend on the mandrel material used. The stiffness of the mandrel material would have a direct effect. Hoop windings on a steel mandrel would show little residual stress when removed from the mandrel, whereas the same type of winding on a eutectic salt or

plaster mandrel would yield residual stress in the hoop windings in the order of 5,000 psi.

Mandrel reinforcements must be designed to minimize deflection. The material used should be capable of maintaining dimensional tolerances set up by the requirements of the wound part. Generally, the mechanical properties such as compressive strength and tensile strength will fall off with temperature. Mandrel designs have to take into consideration these property requirements, so that efficient lightweight mandrels are produced.

Mandrel Design

In considering the differences between "wet" and "dry" resin systems, it is also necessary that attention be given to the basic difference in mandrel design. This difference is the need to heat a mandrel during winding with a "dry" system but not with a "wet" system. Both systems, of course, require a mandrel capable of sustaining curing temperatures and, for closed-end vessels, one that can be removed following cure. Because of the high winding tensions usually employed, mandrels must be designed to resist very high collapsing pressures. This factor will tend to limit the choice of materials that can be used. Any mandrel must (1) sustain working loads incident to winding, (2) maintain a reasonable dimensional integrity throughout its operational life, (3) withstand curing temperatures without degradation, and (4) be subsequently removable.

Concerning wet impregnating, various mandrel materials currently in use satisfy, in varying degrees, the requirements just given. No one has discovered a material to accomplish all the objectives, but materials currently in use belong to the following groups.

1. *Eutectic salt.* Heated to melt and slush-cast to provide a shell. Dissolvable with hot water and agitation.
2. *Soluble plaster.* Cast to provide a shell. Must be predried before use. Mostly dissolvable with water, usually coming out as a milky liquid with chunks of undissolved plaster.
3. *Eutectic metal.* Heated to melt, slush-cast, or skin-chilled to provide a hollow shell. Removable with live steam. Vessels with small openings require final X-ray to detect unmelted islands of metal still clinging to inner wall.

The dry system, for which the mandrel must be heated during winding, generally needs some sort of heating element imbedded in the mandrel. This element may be either tubes for steam, superheated

oil, etc., requiring swivel joints for entering and exhausting fluids from the revolving mandrel, or electrical-resistance heating parts, requiring commutator-type slip rings to provide an electrical connection to the revolving mandrel. They are all potentially troublesome. The expense of the revolving heat-energy connection itself can be minimized by integrating this joint with the winding machine design.

The cost of imbedding heating elements or tubes in a mandrel that must be expendable is high. Some attempts have been made to modify this requirement by eliminating tubes, for example, by merely flooding the mandrel interior with a heat-transfer fluid. The fluid could be chlorinated diphenyl or "Dow Therm." Steam is not practical because of dangerously excessive pressures at curing temperature. Other methods, such as dielectric heating, field association, etc., have not yet proved practical. The following materials are now in use.

1. *Eutectic metal.* Flexible insulated wires are tied in place in the casting mold, after which the liquid metal is cast to form a shell including the wires. Flexible tubes or metallic hose can be used also. Either medium must, of course, be sufficiently flexible to allow removal after the mandrel shell has been melted out.

Figure 5.12a Collapsible plaster mandrel for filament-wound vessels. (Courtesy of Lamtex Industries, Inc.)

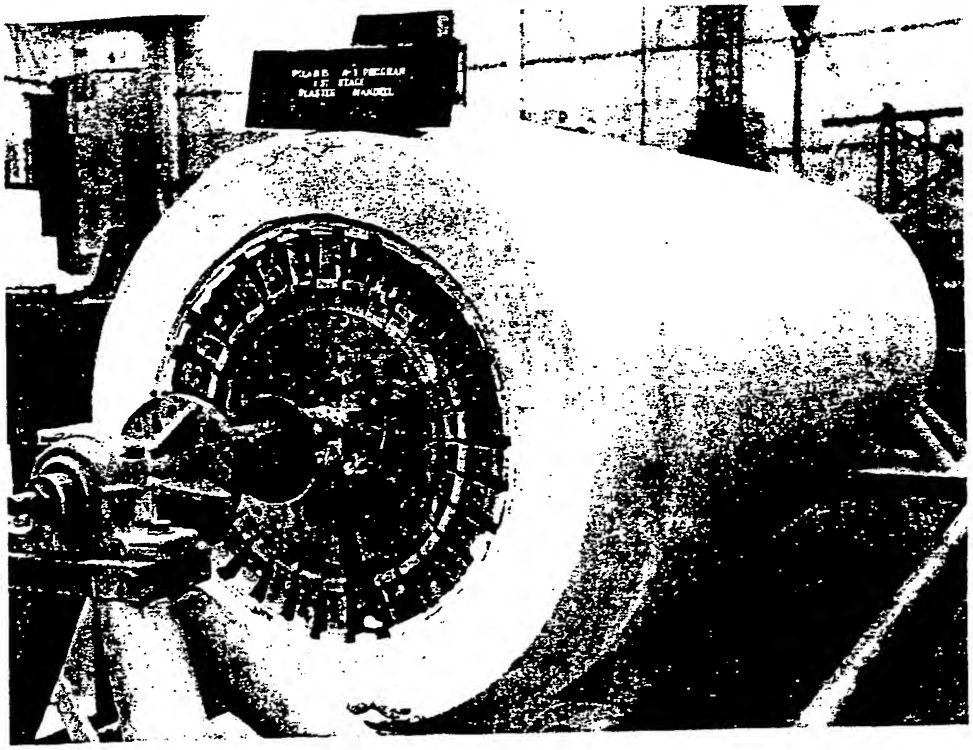


Figure 5.12b Aft view of plaster swept aluminum segmented mandrel in its handling cart. (Courtesy of Aerojet-General Corp.)

2. *Soluble plaster.* Heating members are treated in the same manner as the eutectic metals. Care must be taken to avoid large temperature gradients between heating elements and the plaster matrix which will cause thermal-stress cracking and spalling.
3. *Cast aluminum.* If it is geometrically possible, half-shells are cast from nearly pure aluminum, for example, 1,100. Heating members are cast integrally but with the provision to bridge the parting line. Half-shells are thereafter put together to provide a hollow mandrel. Following cure, the aluminum is simply eaten away with a caustic solution. In order to protect the laminate, a barrier, such as rubber, is required on the outer surface of the mandrel. This method gives excellent heat transfer and is structurally sound throughout the life cycle. It is, however, costly and has a very high coefficient of thermal expansion.

Breakaway plaster mandrels are used principally to fabricate large units or complex shapes. When large plaster mandrels are used, a metal arbor is incorporated. Sectional metal units are usually imbedded in the outer section of the plaster mold.

Structures are sometimes fabricated with unsymmetrical sections. For example, the walls of the Thor missile fuel tank consist of a fluted sandwich construction. Two filament-wound tubes are separated by vertical epoxy-glass fabric stiffeners which resemble a multitude of I-beams separating the inner and outer filament-wrapped tube wall. This type of a part can be fabricated by the lost-wax process.

The wax is a mixture of beeswax and paraffin. It has a melting point of approximately 165°F. The wax can be extruded in a variety of shapes, but ordinarily, a rectangular cross section is used. During the extrusion process, the wax is spirally wrapped with a resin-impregnated fabric tape. The wax becomes a mandrel for the resin-glass outer structure.

These wrapped mandrels are used directly in the winder. After the inner skin of the container is wound, the mandrels are positioned either axially or circumferentially on the skin. When the inner surface is completely covered, the outer filament-wound structure is applied.

The cure cycle for the sandwich structure is kept below the melting temperature of the wax. After the part is cured, the complete part is subjected to a temperature above 165°F so that the wax will drain out of the structure through predesigned openings.

When only a few parts are to be made, the general procedure is to design noncollapsing mandrels. This procedure results in lower costs. In vessels where the dimensions of the part are such that mandrels cannot come out in one piece and collapsible mandrels are uneconomical, either melt-out, dissolve-out, breakout, or inflatable mandrels may be employed. In all designs a major engineering effort is made in order to allow for the winding loads, curing cycles, resin shrinkage, and maintaining the desired dimensions.

An example of a rather intricate production, low cost, and large mandrel design is for the Polaris A-3 first-stage cylindrical motor chambers. Aerojet Corporation uses collapsible segmented aluminum mandrels. These mandrels are more expensive than the built-up disposable units used in development programs. The initial cost is justified on the basis of reuse. This mandrel is designed so that its assembled configuration is slightly smaller than the inside contour of the fabricated case. The difference is made up by a thin wall of plaster swept over the mandrel to the final inside contour.

Curing

Polymerization of composites on a mandrel is generally performed by applying heat during and after winding. The temperature to cure

the resin can range from 200°F to 330°F. The actual temperature is dependent on resin used and on whether resin is modified with hardeners or accelerators.

Specific curing cycles for the wet resin or prepreg systems are discussed in the resin chapter. In general, infrared-heat or steam-heated jackets are located around filament or roving just before it is applied around the mandrel. In the wet layup system, heaters are sometimes used next to the resin reservoir, where the resin is picked up by the moving filament.

External heat can also be applied so that it is concentrated on the wrapped material during the winding operation. Internal heat within the mandrel is also applied particularly for containers which are large in dimensions or have thick wall sections.

After the containers are wound on their respective mandrels, final cure generally takes place in an oven. The ideal situation is to cure the container while it still remains on the mandrel. It is also desirable to cure the unit so that its main longitudinal axis is in the vertical direction and the case is slowly rotated in the oven to assure even heat distribution.

Pressure Chambers

Present methods for curing structurally efficient wound systems generally require curing pressure ranging from 50 to 1,000 psi in addition to heat. Pressure curing for the larger units is being conducted in autoclaves and hydroclaves. However, with the advent of larger rocket solid-propellant boosters being designed, new pressure systems are being explored. Diameter sizes are being considered which range from 156 to 540 inches.

Pressure curing chambers to handle higher loads are not available. Since industry experience is not available for the larger chambers, the cost of developing and building them would be exceedingly high. New pressure concepts are being evaluated such as *deep-submergence, form-fitting,* and *cable-clave* systems (6).

In the *deep-submergence* system, the wound unit contained in a rubber bag or boot is lowered into the ocean. Hydrostatic pressure is applied. One approach is to accomplish winding in a waterside facility. Waterside facilities are now being set up to load the large motors with propellant so that they can be transported over water. After wrapping and covering with suitable materials, it is taken out to sea by boat.

The assembly can be lowered to a depth equivalent to 200 psi. At

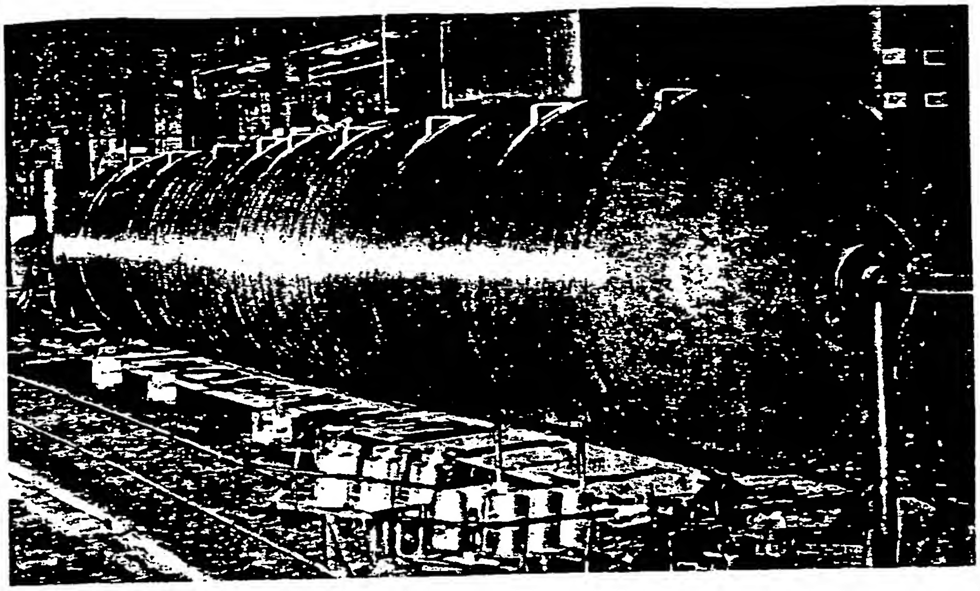


Figure 5.13 Longitudinal reciprocating carriage contains and delivers glass epoxy to tank cylinder 9 feet in diameter by 55 feet long. (Courtesy of Black, Sivalls and Bryson, Inc. and *Reinforced Plastics*.)

this depth the electrically heated mandrel is raised to a temperature of 180°F. After a precure cycle time period the assemble is lowered to the desired pressure depth. During this descent the mandrel temperature is raised to the required temperature. After the cure cycle is completed, electric power is cut off. The assemble can be cooled at depth pressure before it is raised.

The *form-fitting* pressure vessel is particularly well suited for non-cylindrical wound shapes such as conical nozzles. Stacks of steel rings can be assembled which are progressively smaller in diameter with contour that matches the outside mandrel form. These rings can be dowelled together. Its ends are capped with terminal plates and in turn bolted back into the internal steel mandrel structure.

In the *cable-clave* system a continuous steel cable supplants the steel rings. This assembly consists of a rubber boot covering the glass-wound layup, which is on the mandrel. In turn a second rubber boot encloses the first boot. Before wrapping the second boot with the cable it is wrapped by a thin mild steel tape. A rosette-shingle pattern is used with this tape so that it will protect the boot during cable winding and also restrict the rubber from extruding between cables. Water is pumped between the boots.

The entire cable assembly can be heated under pressure in an oven

or by using steam or electric heaters in the mandrel. This system has already been used with hydrostatic pressures reaching 2,000 psi. The cured large parts have produced quality controlled high-density materials which almost meet theoretical optimum.

TENSIONING FILAMENTS OR TAPES

The degree of tensioning in fibers or roving during the winding operation is important (Table 5.1). This tension should be as uniformly distributed as possible over all fibers. For certain shapes as well as types of winding machines, uniform loading can be accomplished more readily by using low-end-count rovings individually tensioned in combination with textile camelback or scissor conveyors which reduce the number of bends in fiber or roving.

An important factor to consider with regard to fiber tension is that when thick-walled vessels are being fabricated in one winding operation, the tension should decrease proportionately as the wall thickens. If the tension is not reduced, the tendency will be to compress the inner fibers, or, if the wall is of sufficient thickness, the inner fibers will carry practically no load.

One method of tensioning fibers is to apply a mechanical brake to the glass spool. The glass fiber in turn passes through a series of stationary or braked polished-steel rollers. One or more of these rollers can be made adjustable so that variation in tension can be controlled.

***Table 5.1** Relationship of Glass Roving Machine Tension to Resin Content and Hoop Tensile Strength*

Machine Tension in Roving, lb	Resin Content, % by Weight		Hoop Tensile Strength, psi
	Prepreg Roving before Wrap	Cured Ring	
6	18	18	253,000
12	18	16	260,000
18	18	15	251,000
18	16	16	260,000
18	22	19	251,000
18	25	19	216,000
24	18	15	236,000

Test ring 3-inch diameter; 0.060-inch-thick wall.

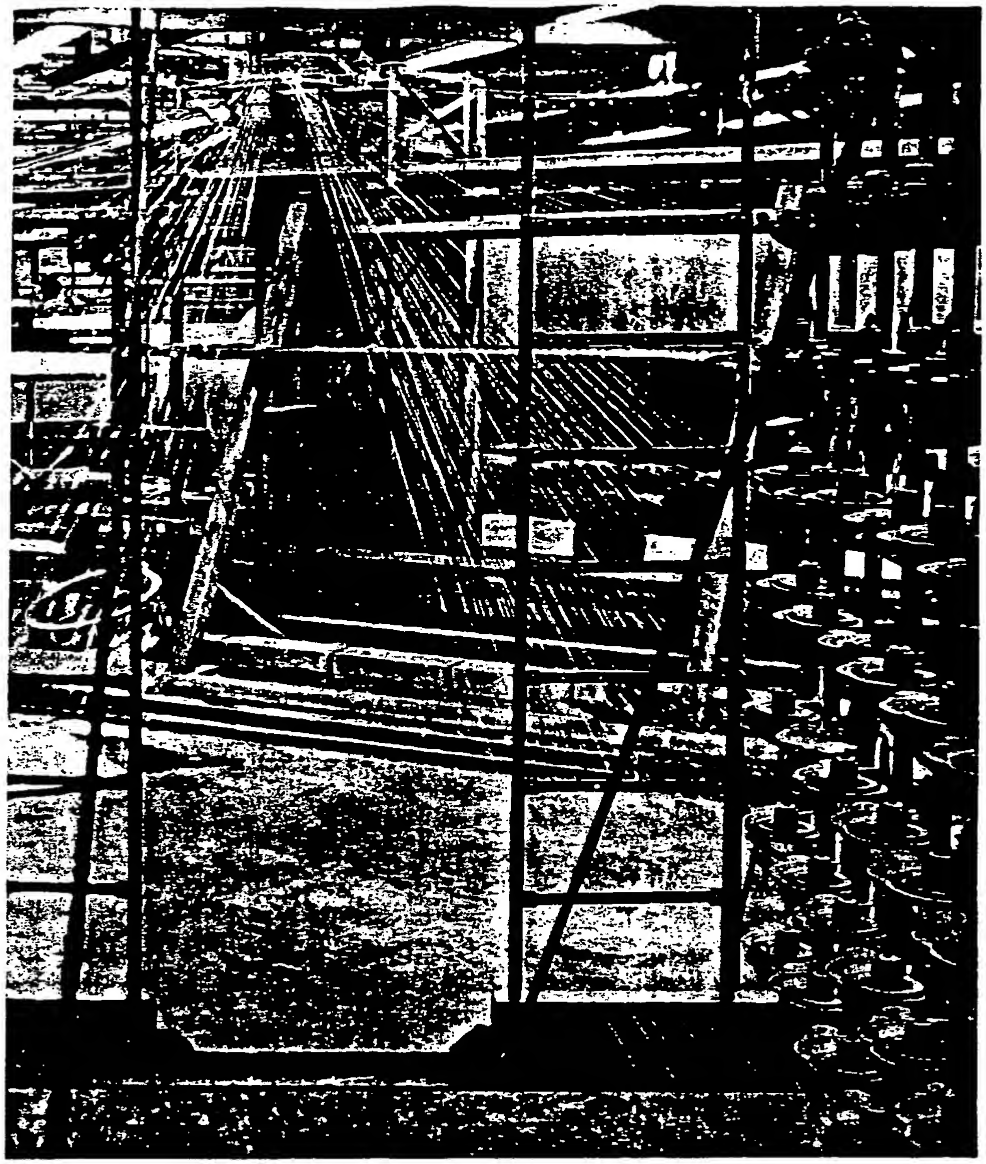


Figure 5.14 Glass fiber creel which supplies winding machine using hysteresis tension controls on fiber glass fiber creel supplying reinforcements to winding machine; hysteresis tension controls are applied to each reinforcement via their spools. (Courtesy of Lamtex Industries, Inc.)

During the movement of the filament through tensioning rollers, the individual fibers remain separated by the inclusion of combs to prevent twisting, bunching, and fraying. The use of small rollers (minimum diameter should be approximately 2 inches) or too many rollers can also cause fibers to fray or reduce mechanical properties.

Too many rollers will result in the glass fibers bending and losing an appreciable amount of strength. Final tension can be applied to the fiber as it is fed over the curved guide tongue which directs the rovings to the mandrel. Between the last roller and the guide tongue, a tension meter can be fitted in order for the operator to visually control tension. This meter can also be set up so that automatic tension control can exist.

The fibers can be tensioned in two places, either at the spool or between the spool and the mandrel. The simplest place to provide

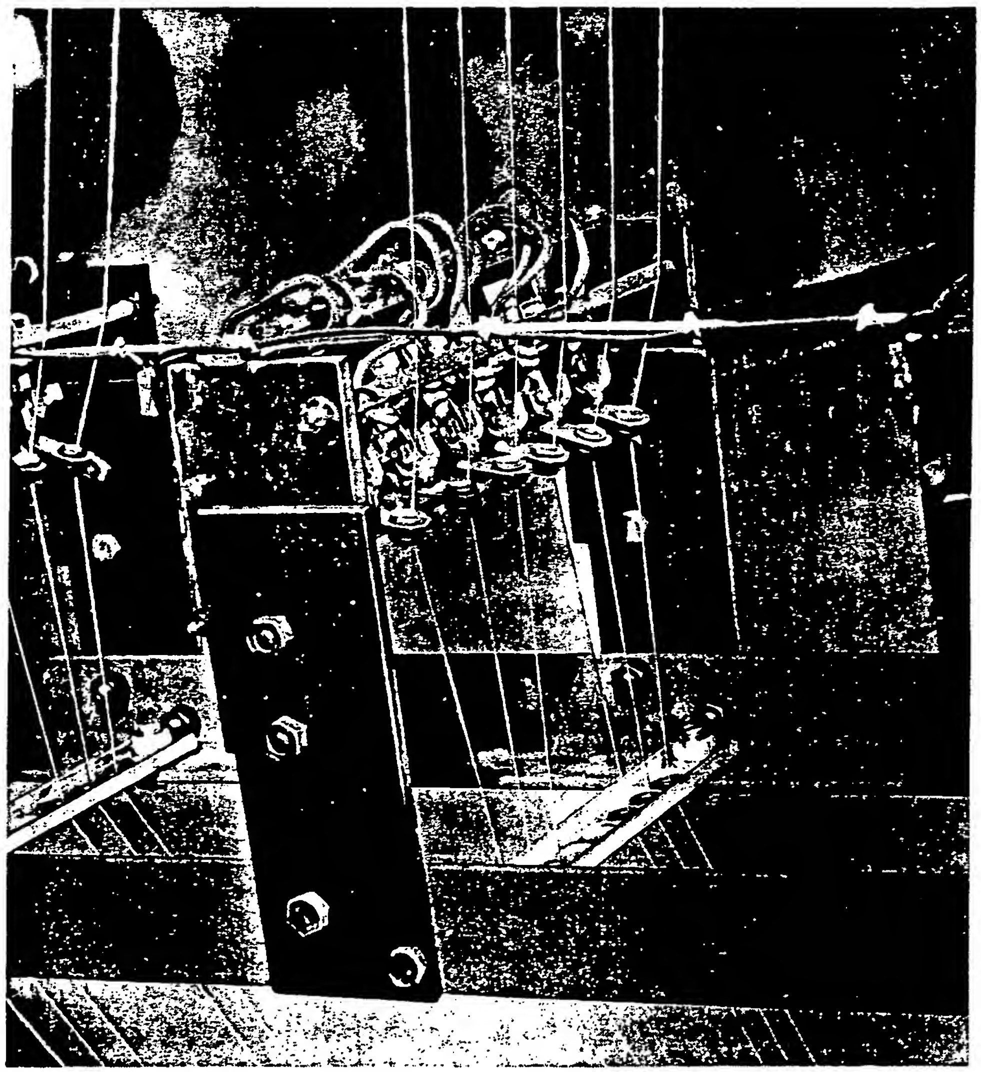


Figure 5.15 Filament end-breakage control. (Courtesy of Lamtex Industries, Inc.)

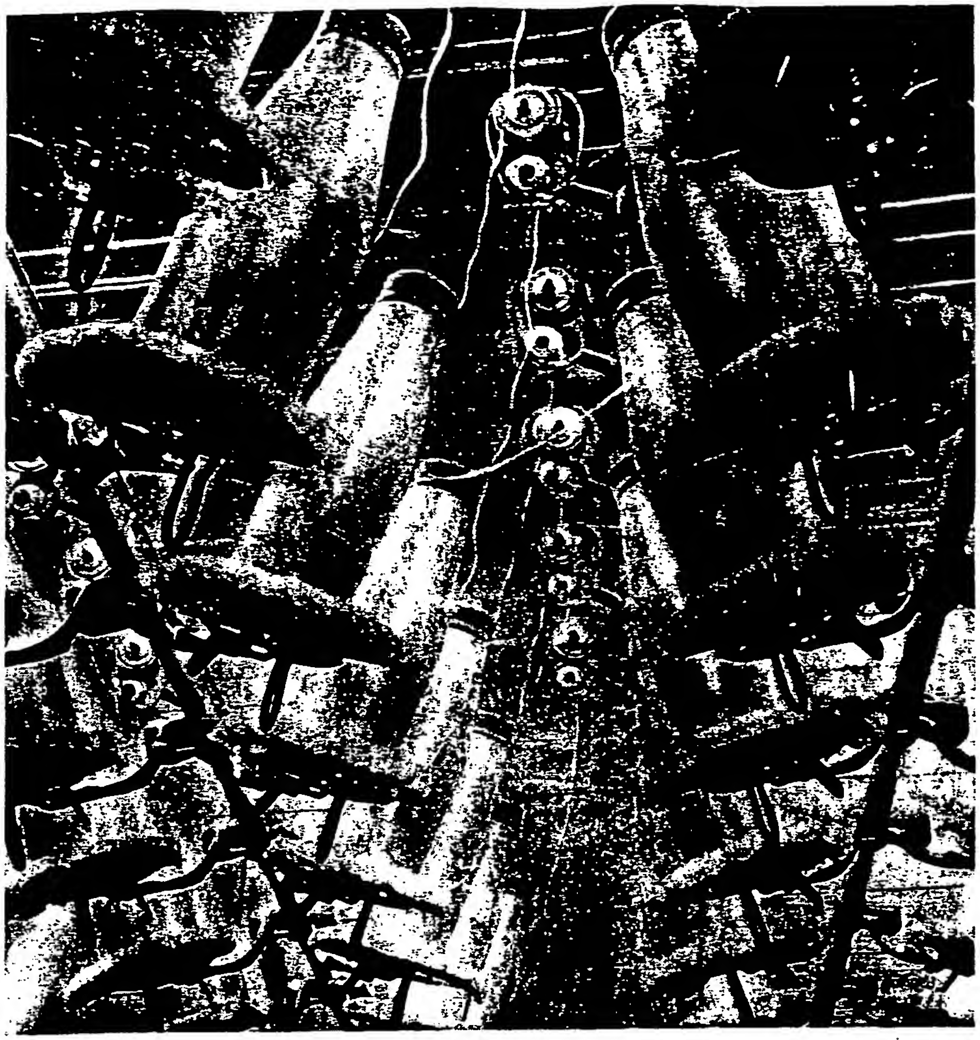


Figure 5.16 Glass creel support used for shotgun production. (Courtesy of Olin-Mathieson Chemical Corp.)

tension is at the spool. However, either method sets up complications. In a wet system, tensioning at the spool makes it difficult to impregnate, while in a preimpregnated system, if the material is not packaged correctly, it will cut down into the package. Tensioning between the spool and the mandrel can also result in difficulties, since further handling of the fiber is necessary. It is believed desirable to tension wet roving after it leaves the impregnated box and to tension preimpregnated roving on the spool.

It is important that during the winding operation, controlled tension is applied to the filament. The important function of tensioning is to control the resin content and properly align the filaments on the

mandrel. With insufficient or uncontrollable tension, loss in structural strength can be as high as 30 per cent.

Controlled winding tension to produce high-strength parts is particularly applicable when wet resin systems are used. As previously mentioned, the tension alone controls the resin content. With the preimpregnated materials, tension control is necessary in order to produce dense-void-free parts.

The use of tapes in winding machines is more desirable, particularly in the large containers or in special applications such as re-entry ablation nose cones. More material can be applied during each rotation. Tapes can be made up during the wrapping operations where filaments or rovings are individually resin coated. In turn they are fed through a series of rollers to produce any width tape. Prepreg tapes are also available. In addition to using filaments or rovings the tapes can be made of nonwoven felts or woven fabric reinforcements.

Prepreg tapes have been used in a wide variety of configurations as reinforcing materials around ports in filament-wound structures. The majority of these configurations consist of strips of the tape laid in equal intervals around and tangent to the circumference of the port.

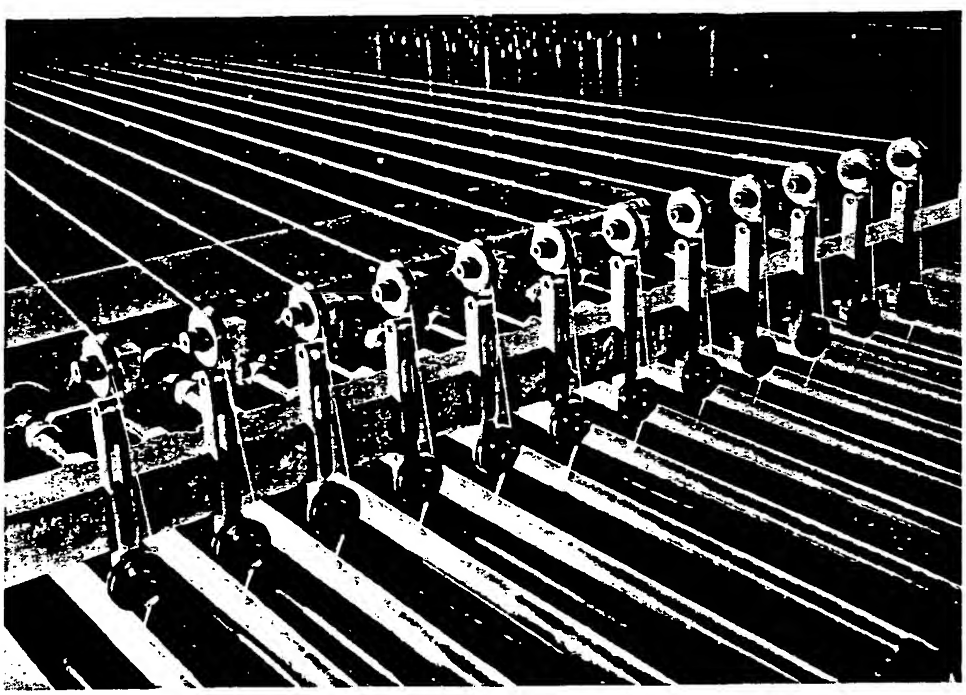


Figure 5.17 Filament-winding set-up for shotgun barrels. (Courtesy of Olin-Mathieson Chemical Corp.)

Tapes oriented tangent to the circumference are desirable for resisting the axial forces. The overlapping of the tapes provides ample cross section to the reinforcement to resist the bending and shear forces. They can also be oriented to provide extra cross-shear strength under the ports.

A problem in using tapes around the ports is that of determining the precise orientation to give maximum strength and minimum weight. Detailed analytical work and testing is required to produce the most efficient tape layup. In general these tapes are fabricated on a form having the same contour as the structure to be fabricated. By using this procedure the tape follows closely the winding mandrel contour.

END CLOSURES

Filament-wound pressure vessels always require some type of end closure or end fitting. Certain vessels such as large rocket motor cases require multiple nozzle end closures. In some applications, simplified techniques can be used whereby metal or plastic end closures can be bonded during or after the winding operation. In some of these applications, high shear strengths can be developed by properly designing the end closures.

In tape or ribbon-wrapped wound motor cases, the only practical method for attaching end closures is to use structural adhesives. The end closures can be designed with a cupped section which can either form a lap or scarf joint. Where extreme high internal-pressure loads are to be developed, lapped joints will be required. New adhesives are being developed specifically for this type of application. The adhesives will have a varying structural load capacity from one edge to the other.

The more conventional technique for attaching end closures in filament-wrapped cases is to helically wind the filaments over the end closure fitting so that there is pure tension in the fibers. Unquestionably, the most difficult and weight-consuming problem involves properly designing integral end closures. No reinforcement weight allowance is required for openings centered on the case axis, provided both ends are of equal size. A wrapping pattern can be selected so that the filaments always pass tangent to the openings.

LINERS

In certain applications, such as solid rocket motor cases, an inside thermal insulator on the filament-wound structure is desired. It is

sometimes feasible and advantageous to apply this insulation material around the mandrel prior to the wrapping operation. In this way the cure of the insulator as well as the filament structure can be accomplished at the same time. This type of cure cycle results in an integrated insulation with the case wall. The insulators can be made of homogeneous rubber-plastic sheet or reinforced plastics. The types of reinforced plastics include high resin-treated glass tape, phenolic-asbestos tapes, etc. (7).

Highly stressed filament-wound plastic tubes do not readily resist the passage through them of fluids under pressure. When leakage problems exist, it is necessary to incorporate within the wound tube a liner of an impervious material. Metallic liners are sometimes considered. However, it is important when metal is used that the expansion characteristics of the metal in plastic be similar. In order to reduce problems when metal liners are incorporated, flexible adhesives are used between the metal and plastic.

The most useful lining material has been rubber or plastic. Various forms are available in order to meet different fluid or internal conditions. The flexible type of liner only has to meet internal operating conditions. No stress loads are applied to the liner.

INTEGRAL CASE WINDING

Integral case winding is a manufacturing process well worth the consideration of the designer of pressure vessels for solid-fuel rockets. Various organizations have been developing this system. This process comprises the integration of the propellant grain, the insulating components, and end-closure details (8).

The disadvantages of this type of system are the hazardous nature of this winding operation plus the difficulty and hazard of curing the thermosetting resin after winding. However, it is generally considered that the winding operation is perhaps a safer procedure than the technique of machining solid propellant grains. The winding operation suffers no particular disadvantage if isolated. Various resin systems are now available which permit curing of the filament-wound structure below the hazardous temperature (generally from 160°F to 210°F).

The major advantage of this procedure is the ability to inspect the propellant casting prior to providing the unit with the necessary insulation and rocket motor case. At the present time the propellant is cast into a completed case. This procedure requires elaborate inspection techniques and expensive methods to remove and recast any

reject castings. With the integral case-winding method, only acceptable castings are completed by filament winding the required rocket motor case.

Another advantage gained by this technique is the absence of internal strains in the propellant when it is cast into a fixed-size rocket motor case. With a fixed case, an adhesive is used to fix the propellant to the case to prevent the formation of a gap between the two. The inability of the propellant to shrink or reduce in size during casting sets up internal strains in the propellant. These strains, when augmented by the strains caused by the differential thermal response, have often proved catastrophic. With an integral system, the casting shrinkage has occurred before the case is filament wound over the cast propellant. In addition, the filament-wound system can be fabricated to shrink on the propellant and thus minimize the differential strain between the propellant and the rocket motor case at low service temperatures.

Although some propellant grains are not perforated along the axis to allow for a supporting spindle, it is still considered feasible to wind on them by using devices such as broad rollers or resin-lubricated slippers for external intermediate support of the assembly to be wound. Such supporting devices have been used when long parts are being wound.

FOLDABLE CONTAINERS

Future space programs will require launch and flight vehicles with very large overall dimensions. Since only limited-size vehicles can be transported from manufacturing to launch sites, research and development programs have been conducted to study methods of manufacturing foldable and storable filament-wound reinforced glass fiber tanks and containers. The manufacturing principles and techniques developed follow universally recognized manufacturing methods and are of such scope as to be applicable to different types of pressure vessels or tanks for liquid or solid propellants (9).

The tests conducted to validate the feasibility of a manufacturing method indicate that full-size tanks could be more easily handled and would, consequently, be more reliable end products than the model-size tanks used in the tests. These tanks consist of a filament-wound barrel and the end skirts. Different from ordinary tanks, gas-tight liners are applied on the inside and the outside of the tank so that the entire tank wall is covered.

The inside liner may be preformed, or it may be sprayed over the

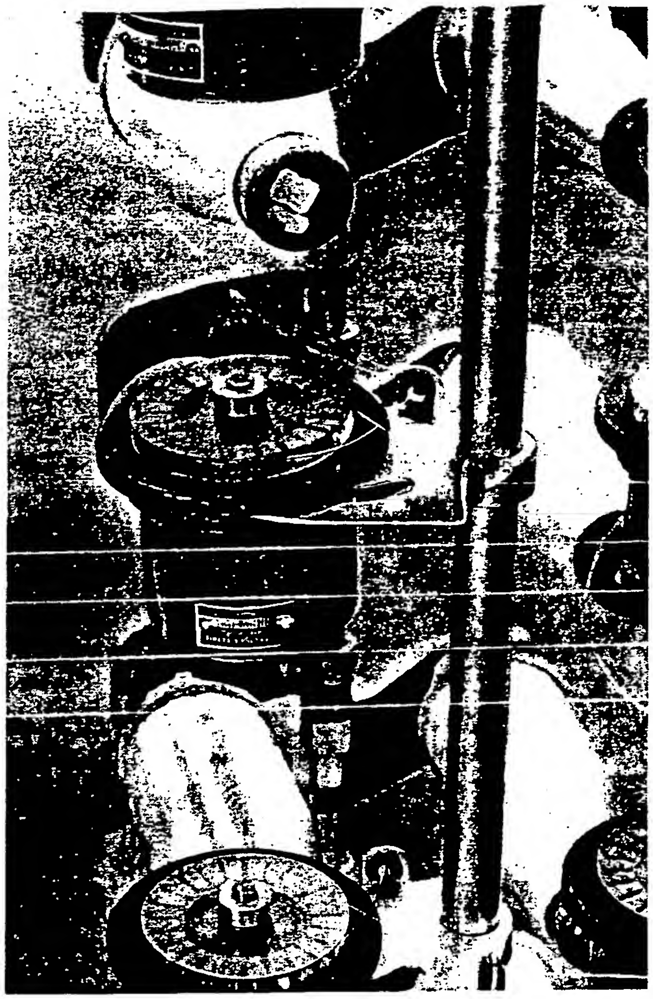


Figure 5.18 Filament hysteresis tension control used in creels. (Courtesy of Lamtex Industries, Inc.)

mandrel surface; it may also be retained as corrosion protection for the tank wall. A removable plastic bag may serve as the outside liner when an outside protector is unnecessary.

The preimpregnated filament or prepreg material may be wound into the tank form in the customary way, that is, around a removable mandrel that is contoured to the inside of the tank. The manufacturing procedure is started by covering the mandrel with the inside liner. The tank wall is wound with the composite filament, and the skirts are attached.

When the tank wall has been wound to the final thickness, the thinwalled, gastight plastic bag on the outside wall is constructed.

If it is to remain as a protection against corrosion, this outside bag has to provide a snug fit. The following operation is to apply a vacuum between the inside liner and the outside bag. After vacuum is obtained, the open end of the sandwich configuration is sealed to sustain the vacuum. The mandrel is removed without injuring the inside liner or the outside plastic bag. Experience has already shown that the mandrel can be removed without disturbing filament alignment. Depending on the self-curing characteristics of the resin used, the glass fiber wall will remain flexible for a specific time.

Folding the soft and flexible tank is the most difficult procedure and requires special care. The folded tanks can be stored and transported in refrigerated containers in order to eliminate polymerization of the resin.

These folded-flexible tanks can be internally pressurized and cured with heat when they are ready to be used. This particular development has interesting potentials for use in manufacturing tanks when they are required immediately, but the process also has potentials for erecting containers in outer space. They could be launched in the folded position. After outer space is reached, they can be erected and cured by techniques presently being used to erect expandable systems in outer space environments (10).

References

1. J. B. Rittenhouse, W. G. Jurevic and E. E. Morris, SAMPE Symposium, Section 19 (June 1963).
2. W. B. Goldsworthy, "Filament Winding Box Like Structures," Ferro Corporation, Torrence, California (February 1963).
3. N. A. Beaucamp, Narmco Research and Development Engineering Report, No. G1-E3 (January 1961).
4. J. V. Kindall and S. E. Susman, "High Temperature Resin System for Glass Filament Wound Composites," AF(ASD) 33(616)-6737 (1961).
5. A. M. Shibley, H. L. Peritt and M. Eig, SPI Annual Preprint, P 6A-1 (February 1962).
6. E. E. Hardesty and A. R. Church, SAMPE Symposium, Section 18 (June 1963).
7. J. J. Sewell and J. K. Kuno, SPI Annual Preprint, pp. 7A–1 (February 1962).
8. R. E. Young, University of California course, Design of Fiber Glass Pressure Vessels (July 1961).
9. O. P. H. Dahlke, AIAA Report 2913-63 (April 1963).
10. D. V. Rosato, SAMPE Symposium, Section 4 (June 1963).

6 Factors Affecting Properties

The major problem in designing filament-wound structures lies in the variability of the material. The reliance that can be placed on a given property from item to item is directly dependent on the knowledge of and ability to control the variables which affect end properties. Many of these factors have been identified previously but have not been discussed.

Significant improvements in filament-wound materials and processes have been made in recent years; however, the gap between attainable laboratory strengths and allowable working stresses is widening. Competition with other materials is keen. The future rate of progress is of great concern to all segments of this industry.

Perry (1) has pointed out the problems of increased adoption of filament-winding techniques and the structures fabricated by such means.

> The use of filament-wound reinforced plastics for advanced applications is being impeded by a number of shortcomings in the present state of the art. These fall into two fields: (i) materials shortcomings including impermanence; incomplete knowledge of the microstresses, viscostrains, and fracture mechanics of the materials; incomplete information on the influence of materials properties, design details and process variables on the structural efficiencies, weights, and permanence of complex molded products; inadequate or non-existent codes, particularly for filament-wound internal and external pressure vessels; problems of repair; adverse design limitations and complexities which are usually dictated by over-riding systems requirements; and (ii) inadequate descriptive and classification codes for the materials; inadequate materials test methods and specifications; inadequate classifications of allowable defects in filament-wound products; and inadequate nondestructive test methods for molded parts.

Early in the use of reinforced plastics, the variability and adaptability of the material to suit various conditions of stress and operation were suggested as major intrinsic advantages of this composite type of material. There are many variables which affect the properties, however, and thus control the allowable stresses which a designer must use. Precise quality control and careful operational techniques will aid in prevention of loss of strength. Some of the factors affecting properties of filament-wound structures are discussed in the following sections.

FABRICATION VARIABLES

Variations in the amount of resin used in reinforced plastics occur because of variations in pressure applied during winding and/or curing. Compressive properties are relatively unaffected by variations in resin content. Tensile and flexural properties decrease with increasing or decreasing resin content in respect to optimum. This loss in strength is usually directly related to the increase in the thickness or development of voids in the laminate. Resin coatings are sometimes applied to the surface in order to improve appearance. However, with relatively thick surface coatings of resin, cracking under outdoor environmental conditions can occur because of differences in coefficient of expansion between the coating and the laminate.

In order to expedite the cure of the resin after the winding operation, the rate of temperature rise is sometimes increased. The effects of such changes in procedure are important since they can significantly affect strength properties. There is generally an optimum curing time for maximum strength for each rate of temperature rise. The rate of cure in properties of a laminate can be changed by varying the type and quantity of curing agent. With certain resins, small changes in type and quantity of catalyst have an important effect on the properties of a cured laminate. In other resin-catalyst systems, the polymerization of the resin is accomplished satisfactorily with less exacting requirements. The choice of curing agents has a significant effect on the strength properties of epoxy laminates, particularly at elevated temperatures. These curing agents also vary electrical properties significantly.

Certain types of resins require an after-baking or post-cure. This is especially necessary in applications where strength properties are important at elevated temperatures. The post-cure also prevents blistering or delamination during high temperature service. Post-curing must be conducted in accordance with approved procedures,

since factors such as rate of post-cure, glass finish, and curing systems affect the properties of a laminate.

PROCESSING VARIABLES

The variables in processing which affect final properties can be summarized as follows: control of winding pattern; control of filament tensioning and handling of fibers for minimum damage; control of reinforcement-to-matrix ratio; programming of equipment to obtain maximum performance for the material used; standardization of equipment; design of equipment so that it can be readily adapted to different lengths and diameters; flexibility of equipment for handling a variety of reinforcements such as prepreg, tapes, wire, and ceramics; and reproducibility or quality control.

The properties of the composite material are determined not only by the component materials but also by the manner in which they are used to fabricate the final product. Fabrication techniques therefore

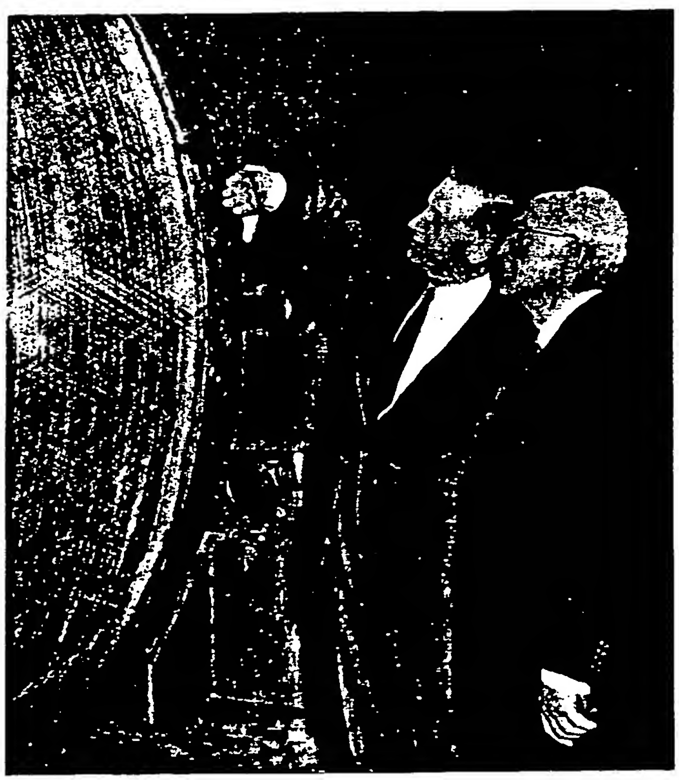


Figure 6.1 Corner view of large wound tank. (Courtesy of Black, Sivalls and Bryson, Inc.)

intimately affect the material properties and the service life of filament-wound products. Fabrication variables such as winding, tension, resin content, twisting, glass handling, resin temperatures, curing schedules, and others have an influence not only on the mechanical properties but also on other physical properties. The important physical properties affected are density, size of voids, distribution of voids, and thermal and electrical conductivity. The most important process parameter is the winding pattern, it determines the directional properties of the composite. The pattern also has a great influence on density, thermal and electrical properties, and fatigue.

WINDING VARIABLES

In winding cylindrical pressure vessels or rocket motors, two winding angles are generally used. One angle is determined by the problem of winding the dome integrally with the cylinder. Its magnitude is a function of the geometry of the dome. These windings also pick up the longitudinal stresses. The other windings are circumferential or 90 degrees to the axes of the case and provide hoop strength for the cylindrical section.

It is possible to wind domes with a single polar port integrally with a cylinder comparatively easily without the necessity of cutting filaments. However, a practical solution of winding multiported domes has not yet been achieved. Cutting is obviously not desirable, since it interrupts the continuity of the basically orthotropic material. The usual procedure in winding multiported domes is to add interlaminate reinforcements during the winding operation where the ports are to be located.

It has been explained that it is possible to wind integrally most of the bodies of revolution, such as spheres, oblate spheres, and torroids. Each application, however, requires a study to insure that the winding geometry satisfies the membrane forces induced by the configuration being wound.

SIZE VARIABLES

It is reasonable to assume that large filament-wound structures cannot achieve a stress level as high as small units. Basic material and manufacturing variables form the basis of this reasoning. One of the major assumptions for this scale effect is generally related to the deviation from the thin wall—membrane theory of pressure vessels (2). The literature reports that in addition to pure tension, the thicker

Figure 6.2 Wound 22,500-gallon tank being transported to railway assembly plant. (Courtesy of Black, Sivalls and Bryson, Inc.)

walls are also subjected to high interlaminar shear loads. Preliminary evaluation with specimens of varying thickness-to-diameter ratios do not support this assumption. Test specimens having a thickness-to-diameter ratio between 0.005 and 0.020 do not show any definite disadvantages produced by thicker walls.

Basic studies have been conducted on material versus thickness. The results show that with the proper preparation of the base reinforcement and resins followed by controlled curing cycles no reduction in properties occurs. Therefore, it is believed that any reduction in strength levels of large cases will be due mainly to engineering and process deficiencies. They cannot be attributed to the scale effect or to material behavior.

MATERIAL VARIABLES

Fillers

Fillers in the form of finely divided inert material are sometimes added to the laminating resin. These fillers are generally used to improve the bond between resin and glass, to reduce shrinkage crazing of the resin, to provide tacky resin, to reduce thermal coefficient of expansion, to reduce or eliminate leakage, and to increase mechanical properties. An example is the inclusion of asbestos fibers to reduce crazing, reduce leakage, and to increase toughness (3, 4).

Sp cific Gravity (V ids)

The specific gravity of glass reinforced laminates depends on the specific gravity of the glass, the specific gravity of the resin, the resin content, and the percentage of voids. There are indications that the specific gravity of the resin and the laminate is generally slightly different from that of the same resin in cast form. The estimation of laminate densities, percentage of voids, and the like, based on the gravity's component parts, is therefore somewhat questionable. The general procedure is to use the specific gravity of the cast resin in evaluating the composite. Even though this method is not technically completely accurate, it is the most widely used and practical method.

Flammability

Flammability characteristics of glass fiber base materials depend on the laminating resin used. When silicone, melamine, or phenolic resins are used, the laminates are self-extinguishing. Most of the polyester resins are slow burning, with a maximum burning rate of 1 inch per minute. The polyesters can be formulated with additives so that they are self-extinguishing.

Mold Growth

Mold organisms have been observed to grow on glass reinforced plastic laminates. There is little indication that mold growth in itself has any effect on properties. Fungus growth can occur only under conditions of high moisture so that moisture absorption occurs concurrently with fungus growth, and any damage probably arises from the moisture effect (5, 6).

Glass Surface Treatment

For the past two decades, there have been rather extensive study programs to develop improved glass surface treatments. The literature contains many technical reports on this particular subject. Since there are many different kinds of treatments as well as different methods of applying them, it becomes obvious that surface treatments can lead to properties which differ.

Development programs continue in regard to basic studies of the glass-resin interface, the bonding of glass to finish and resin to finish and the pre-reaction of coupling agents with resins. Development of

new finishes are required for the newer fibers (7). This includes the deposition of metal on the glass fibers currently being studied. The present and new treatments being developed require the investigation of the mechanical and physical properties of laminates. Studies include the effects of the modulus of the finish in relation to the modulus of the glass and the resin. The ability of the finish to transfer loads from resin to fiber can be utilized to improve the strength properties of the composite (8, 9).

Toughness and Brittleness

All the reasons why a material is tough or brittle are not fully understood (10). If a material is to avoid the effects of the very high concentrations of stress which occur at cracks and holes, then some type of shear flow must occur locally without markedly weakening the material. Basically, Hooke's law applies. In metals, shear flow is provided by the fact that most metallic crystals can deform along certain planes without becoming weaker. In reinforced plastics, no comparable mechanism exists on a molecular or atomic scale. Certain plastic resins such as polyethylene can deform by a similar sliding action, but this property is associated apparently with thermal plasticity and creep. Rubbers and similar materials are, in an engineering sense, extremely brittle. However, their Young's modulus is so low that they usually avoid the consequences. A crack can run in a stretched rubber sheet as rapidly as in glass. Toughness in reinforced plastics is associated with and controlled to some extent by the adhesion of the resin to the fiber. The surface treatment applied to the glass fiber reinforcement becomes an important control mechanism. Other fibers, such as asbestos, inherently have low shear strength and therefore can produce reinforced plastics that are basically tough and not brittle.

Creep Properties

Tensile creep at room temperature is a negligible factor with glass-resin-reinforced plastics. The ratio of initial to final deformation for a particular time is about the same regardless of the stress level. It appears that stress level has a minor effect on creep rate (11, 12).

Modulus and Shear

One disadvantage of a glass reinforced plastic is its inherent low modulus of elasticity when directly compared to a steel wire. Only

moderate improvements in modulus of elasticity by modifications in glass compositions or in processing appear to be feasible. However, marked improvements in the consistency of the properties of E-glass plastics are possible. Considerable advantage may be gained by this increase in control of the glass properties. Since the major requirement for filament-wound vessels is high stiffness, future structures must take into consideration the new high-modulus fibers now being developed.

In addition to relatively low-modulus values, particularly in the longitudinal direction, the filament-wound structures also have relatively low shear, compressive, and bearing strengths as compared to the most structurally efficient metals. While the shear, compressive, and bearing loads can be kept small in some rocket bodies, in many systems these stresses represent limiting criteria. For example, skirts that connect different stages of a missile system often contain high shear stresses. Rocket motor cases with aft closures that will permit good access to the interior for placing insulation or for casting the propellant are generally not practical in filament-wound structures. The aft closure not only requires a large opening, which complicates the winding, but it also presents a fastening problem, because bolts for closures impose high bearing loads on the case.

Electrical Properties

Filament-wound plastic structures are gradually being accepted as antenna housings for communication, navigation, and radar equipment because of the desirable combination of mechanical and electrical properties. Electrical properties affecting antenna (13) housing design are dielectric constant and loss tangent. For very-high-frequency (VHF) and ultra-high-frequency (UHF) integral antennas, the loss tangent alone is critical. For separate antenna housings (radomes) both the dielectric constant and loss tangent influence electrical design. Factors influencing electrical properties are frequency, composition, moisture absorption, weathering, and temperature. Electrical data for these factors are available and must be considered in design calculations.

In general, the dielectric constant and the loss tangent of glass-resin decrease with increasing frequency above VHF frequencies. At all frequencies the dielectric constant and loss tangent generally increase with rising temperature (14, 15). Some plastic materials show a decrease in these values at higher temperatures. The loss tangent is not affected significantly by changes in the resin content (16). Ad-

justment of the dielectric constant for special applications is accomplished by adding high dielectric constant fillers such as titanium dioxide to the resin before laminating.

ENVIRONMENTAL FACTORS

Weathering

The effects of outdoor weathering vary with climatic conditions. For epoxy, polyester, and phenolic reinforced plastics, the reduction of mechanical properties after periods of exposure up to 3 years is relatively small. Extensive outdoor exposure tests have been conducted in many different areas by military agencies from the equator to the arctic. Various government specifications contain requirements for strength retention in glass reinforced structures of at least 90 per cent after outdoor weathering for periods from 1 to 3 years' exposure (17, 18, 19).

Figure 6.3 Subscale version of a 120-inch-diameter rocket nozzle assembly used to study erosion rates during static test firing; tape winding included in nozzle. Two of the 120-inch five-segment motors will give Titan III-C liftoff thrust of more than 2 million pounds. (Courtesy of Thompson Ramo Wooldridge, Inc.)

Humidity

Glass fiber reinforced plastic laminates absorb moisture when exposed to free water or to high humidity. The amount of moisture absorbed depends on the fiber finish and the resin. Moisture absorption has a direct deleterious effect on the strength of the structure. Indications are that the reduction in strength resulting from exposure to moisture is less in tension and compression than it is in flexure. The greatest rate of this loss occurs in the initial exposure period.

The evolution of study on humidity resistance in pressure vessels began when they were placed in operational service for the F-84F airplane approximately a decade ago (20). These vessels were 870-cubic-inch spheres. Later 2,550-cubic-inch spheres for the F-102 and F-106 airplanes were used. The service pressure of these filament-wound storage bottles was 3,000 psi. All of these units were manufactured with oil and starch sized glass fiber. After several years of service a few field failures were reported, but in spite of exhaustive investigations, no positive proof of the cause of the failures was obtained.

A number of spheres with the same service experience were subjected to conventional cycle and burst tests with the result that none were found to be on the verge of failure. However, it was generally known that starch tested glass laminates seriously deteriorated when they were exposed to severe humidity conditions. In order to eliminate any problems, epoxy moisture barriers were added to the surface of the spheres still in production. In addition a lower stress level was employed on the 870-cubic-inch size. Simultaneously, development work was started on adopting glass fiber with an organosilane finish for use in spherical pressure vessels. A number of changes in winding techniques and other process variables were necessary in order to obtain the same cycle performance with these spheres as with those using oil and starch sized glass. Although organosilane finished glass is greatly superior in moisture resistance, a new moisture barrier was also developed and applied to these latest spheres. The evolution in humidity resistance of glass fiber spheres in terms of number of pressure cycles to failure at 120°F and 95 per cent relative humidity is shown in Table 6.1.

The development of humidity resistance in other glass fiber pressure vessels, particularly solid propellant rocket motors, proceeded along slightly different lines. The earliest experimental work was also performed with oil and starch sized glass. When the organosilane glass finish became available in 1958, manufacturers of these rocket com-

Tabl 6.1 Ev lution of Humidity Resistanc of Spherical Glass Fib r Pr ssure Vessels (20)

Year	Cycles t Failure *
1957	1,000
1959	4,000
1961	13,000

* Pressure cycle from zero to service pressure at 120°F and 95 per cent relative humidity four cycles per minute.

ponents changed immediately to this type of glass. No extra development work was required for this change, since these components needed to withstand only a few pressure cycles. The fatigue problem which slowed the adoption of the new glass finish for spherical pressure vessels was not encountered in rocket case fabrication.

Chemical Properties

When reinforced plastics are subjected to the more common chemicals, there is relatively no effect except that normally expected from absorption. The epoxy resin system is generally used in applications where tanks provide storage of oil field production products (sour crude, hydrogen sulphide, salt water, fresh water, etc.). Other corrosion applications include fertilizer and chemical storage hoppers, pipe, fume carrying ductwork, ventilator housings, stacks, cooling tower frames and grids, scrubbers, and photographic processing equipment.

In the present rocket motor developments, filament-wound containers for solid propellant systems do not principally set up chemically noncompatible conditions. However, in liquid systems, there are problems. The cryogenic fuels and oxidizers used have different effects. In the specific systems using liquid hydrogen and nitrogen, epoxy-glass components are chemically compatible. Most organic materials in contact with liquid oxygen cause explosion or fire hazards. Epoxy-glass composites are chemically and statically compatible with liquid oxygen, but have a tendency to explode when subjected to impact (21). For chemical processing equipment, the corrosion resistance of filament-wound items is influenced by the type of glass rein-

forcement as the plastic. The properties of various types of glass have been discussed by Fener and Torres (22).

To make a glass fiber laminate impermeable, it is necessary to use a liner or barrier film. Since an impermeable barrier has to be used, it is selected to be compatible with liquid oxygen. Liquid fluorine is not compatible with glass fiber. Although compatible liners can be used for fluorine, extreme care is required, for contact of fluorine with glass is a major hazard.

If glass fiber composites are to be used with cryogenic liquids, it is necessary to check the chemical compatibility with both the reinforcement and resins used in the system. Where incompatibility exists, compatible liners are used both on the inside and outside of the units. It is sometimes necessary that the liner be able to stand the maximum strain that the shell will experience under pressure. Usually, liquid-carrying tanks are pressurized and consist of thin sandwich facings stabilized with a core. The facings are designed to take the membrane stresses produced by the pressure and undergo strains of 2 to 3 per cent. This condition results in the liner taking as much strain as the shell at cryogenic temperatures without failing. The necessity of a liner in these composite liquid tanks naturally adds weight when compared to a similar tank made of metal. When considering the overall strength to weight, it has been determined from experience that the plastic version is still more efficient.

Cryogenic Properties

When reinforced plastics are subjected to temperatures such as minus 320°F, strengths either remain the same or actually increase. Data available at liquid oxygen temperatures (minus 297.4°F) show that the properties of an epoxy-glass laminate increased by 175 per cent. With respect to stress concentration, test data show that with notch specimens at minus 297°F lower concentration of stress occur than in similar specimens at room temperature (23).

Reinforced plastics also show good resistance to low-temperature thermal cycling. Test specimens have been subjected to 20 cycles of alternate exposure in liquid nitrogen (minus 320°F) for one half hour, followed by one half hour in air at room temperature. No cracks or delaminations in the material were evidenced after this thermal cycling. These results show that reinforced plastics can be used efficiently at low temperatures. Filament-wound vessels can contain solid propellants and permit large savings in weight when compared to metals.

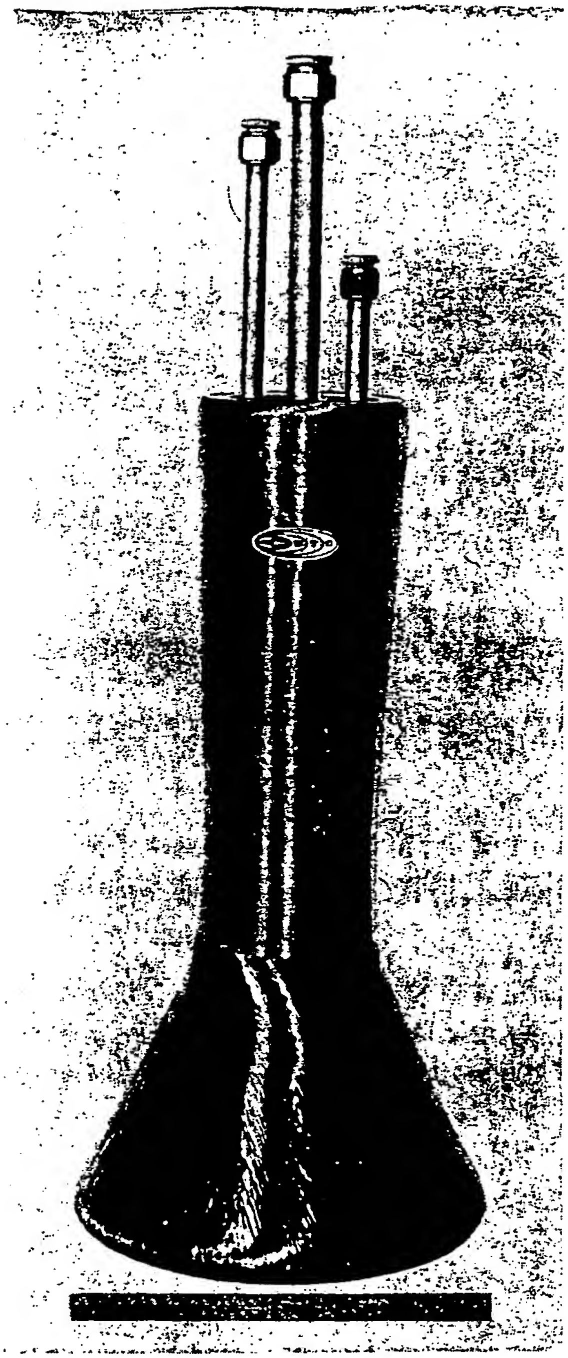


Figure 6.4 Glass filament-wound ablative-cooled thrust chamber is capable of extended firings; high thrust-to-weight ratio is achieved. (Courtesy of United Technology Corp.)

Crazing

Crazing is defined as the formation of fine cracks in a filament-wound structure during load application (24). The effect of craze formation on elastic properties has been investigated, and a preliminary analysis has been conducted as to its effect on ultimate mechanical strength. The results indicate that a potential increase of about 30 per cent in ultimate chamber pressure (burst) is achievable if crazing can be eliminated without degrading the elastic properties.

Elevated Temperature Effects

When considering products such as filament-wound rocket motor cases, plastics can endure an extremely high temperature for a short

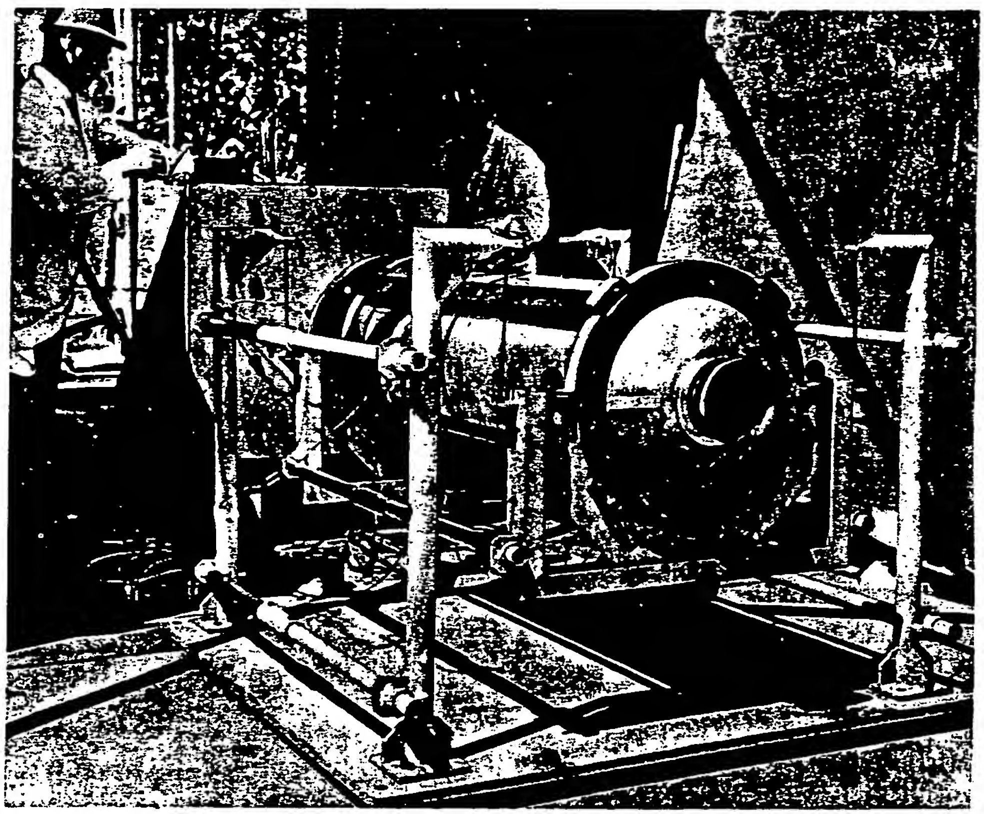


Figure 6.5 Newly developed filament-wound 7-feet-long by 18-inch diameter rocket motor undergoing static firing test produced high overall performance for solid rockets. (Courtesy of United Technology Corp.)

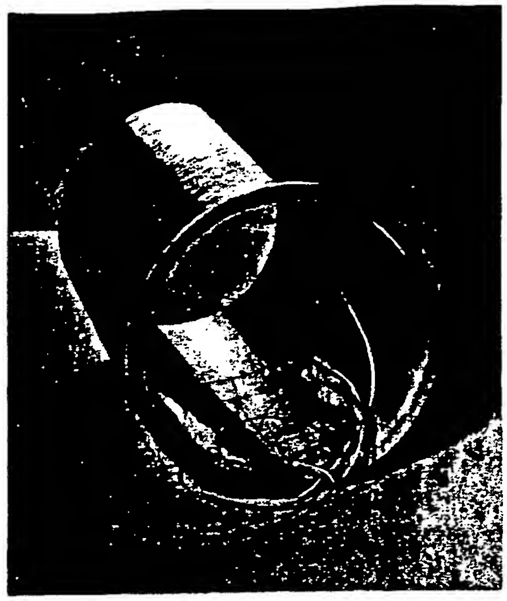


Figure 6.6 Filament-wound heavy wall cylinder instrumented for external pressure testing. (Courtesy of Narmco Research and Development.)

period of time. Temperatures can range from 2000°F to 5600°F for periods of seconds to minutes without destruction of the motor case. Strength and thermal properties of various combinations of reinforcement with organic resins meet these extreme special service requirements (25). When degradation of material becomes a major problem, the wall thickness is designed thicker and/or a thermal insulating liner is incorporated specifically to protect the filament-wound structure (26).

Reinforced plastic laminates subjected to rapid heating may delaminate because of thermal shock (27). It has been found that when it is practical, the laminate should be post-cured to a temperature exceeding that to be developed during thermal shock. By this process, no delamination occurs unless moisture has been absorbed after the post-cure. When considering longer periods of exposure time at elevated temperatures, the strength properties are affected as shown in Table 6.2. Basically, different kinds of resin systems produce different properties.

Glass-epoxy materials show little effect of aging at 400°F for 200 hours. At higher temperatures, the properties are quickly degraded. Almost similar effects on strength properties occur for the heat-resistant phenolic and silicone resin systems. The trend with the phenolic system is to produce higher strengths at higher temperatures when

Table 6.2 *El vated Temp rature T sts n Filament-W und Cylinders* *

Time-to-Temperature Equilibrium, minutes	Ambient Temperature		Outer Wall Highest Temperature, °F	Ultimate † Hoop Stress, psi $\times 10^3$	Hoop Stress, per cent of that at room temperature
	Inner Wall, °F	Outer Wall, °F			
20	285	350	428	104	67.0
25	260	355	447	88	56.7
15	290	360	440	109	70.0
16	295	365	443	96	62.0
23	390	510	597	106	68.4
23	400	510	599	90.5	58.3

* Rocketdyne data (28) on 3 inch diameter samples using heat resistant epoxy-resin E-glass. The cylinders are wound on a 2:1 ratio between hoop and longitudinal wraps. The stress is based on total wall thickness.

† Average ultimate hoop stress at room temperature was 155×10^3 psi.

shorter exposure time occurs. With silicone systems, the trend is towards higher strength at the higher temperatures for longer time periods. Silicone laminates withstand temperatures of up to 800°F for 10 to 30 minutes without appreciable damage.

It should be recognized that as long as the solid propellant is bonded to the shell, the temperature of the shell in the bonded area will not become critical. The propellant itself provides some heat insulation. When propellants are not bonded or are poured directly into the shell, the motor cases may require liners for heat insulation. This requirement exists at present since propellants that burn a longer time have been developed.

The insulation or liner must be capable of taking the maximum temperatures for the firing time period and must not disintegrate or be ripped off the shell under the turbulent flow of hot gases. It must take the maximum strain or elongation of the shell, which is generally in the order to 2 per cent. These liners are generally made up of a type of rubber filled with refractory mineral materials. Tape-wrapped liners, which use nylon or asbestos fiber and modified phenolic resins, are also applicable. The liners generally burn or ablate during the firing. Sufficient thickness of material is provided so that the filament-wound shell temperature remains within safe limits.

Thermal Characteristics

Thermal results for the conventional reinforced plastic laminates over the temperature range of 100°F to 600°F indicate that the prop-

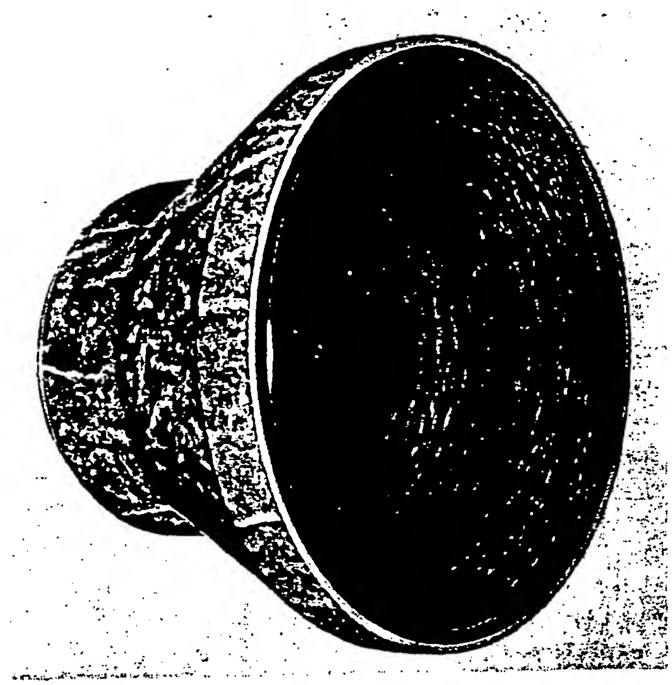


Figure 6.7 Erosion-resistant tape-wrapped matched-metal-molded experimental insulation for the Polaris missile composite exit nozzle. (Courtesy of Narmco Materials.)

erties are but little affected by variations in the reinforcements, resin content, proportion of voids, or the thickness of the laminate (29, 30). However, thermal properties are dependent upon the resin type and the specific test temperature. From 100°F to 500°F, specific heat values average from 0.22 to 0.35 Btu/pound/degree F. For the same temperature range thermal conductivity values go from 0.1 to 0.2 Btu/hour/square feet/degree F/feet. These thermal properties as well as coefficients of thermal expansion for various materials are shown in Table 6.3.

Solar and Nuclear Radiation Characteristics

Values of solar absorptivity have been determined for some heat-resistant plastic laminates. Solar energy spectral distribution both above the earth's atmosphere and at sea level have been reported. The values were obtained by measuring room-temperature spectral reflectivity at wavelengths between 0.3 and 2.4 microns. The ratio of the energy absorbed between these limits to the incident solar energy between the same limits was used to determine the solar absorptivity value. These values, as well as emissivity values, are shown in Table

Table 6.3 Thermal Properties of Materials at a Temp rature of 86°F

Material	Conductivity Coefficient, Btu/hr/square feet/°F/feet	Coefficient of Expansion, 10^{-6} inch/inch/°F	Sp cific Heat, Btu/pound/°F
Filament-wound (epoxy-glass)	0.15	5	0.22
Steel	22.0	6.3	0.11
Aluminum	76.0	12.9	0.23
Titanium	5.0	5.5	0.13
Beryllium	87.0	6.0	0.46

6.4. These values are based on ⅛-inch-thick laminates using No. 181 glass fabric as reinforcement.

The emissivity properties of the material are affected mainly by the color and, to a certain extent, by the finish of the exposed faces. For example, a black surface has a large absorptivity coefficient so that the plastic becomes hot. Although it will emit heat by radiation, the equilibrium temperature may be high enough to affect the plastic. Varying the pigments or coatings alters the emissivity value (31).

With reinforced plastics it is possible to pigment all the way through the material by adding pigment in the resin. Regardless of how the

Table 6.4 Solar and Emissivity Values of Glass-Fabric Composites (23)

Organic Resin Type	Solar Absorptivity: Above Atmosphere	Solar Absorptivity: At Sea Level	Emissivity: Value	Emissivity: Surface Temperature, °F
Phenolic (MIL-R-9299)	0.819	0.808	0.80	254
Silicone (MIL-R-25506)	0.492	0.445	0.83	248
Epoxy (Visually opaque)	0.850	0.830	0.79	230
TAC Polyester (MIL-R-25042)	0.577	0.532	0.82	230

material erodes (ultraviolet radiation erosion, etc.), the color remains constant. This procedure permits maintenance of a constant temperature within the laminate.

Test results have shown that solar radiation causes some sublimation because ultraviolet radiation raises the temperature. This is a function of time exposed.. The combination of solar radiation and vacuum increases the sublimation (32, 33). With respect to the effect of solar radiation on strength, it has been shown that there is little change. This condition exists because of the combination of vacuum and solar radiation. Glass-epoxy laminates exposed to this environment lose approximately 10 per cent of tensile strength after 500 hours.

Nuclear fission reaction releases approximately 10 per cent of its energy as nuclear radiation. The fission products include beta and alpha rays, fast neutrons, and thermal neutrons. Nuclear radiation damage to reinforced plastics is produced mainly by alpha rays and fast neutrons. With respect to distance from the source of radiation, the radiation is attenuated inversely as the square of the distance from the source. The degree of damage by radiation is a function of strength of radiation flux, distance from source, time of exposure, and temperature (34).

Tests and studies show that the effect of radiation on plastics is much more severe than it is on metals. This is mainly because metals have a crystalline structure, with the result that the bonds that hold the individual atoms together are extremely strong and difficult to rupture. In plastic composites the resin is generally not crystalline. Polymerization of resins principally involves a chemical bond that is very easily affected by radiation.

The glass is inorganic, and in a supercooled state it is not crystalline. It is also affected by radiation, but not to the same degree as the resin. Tests show that the epoxy resins when compared with other resin systems have a comparatively high resistance to radiation and do not deteriorate at doses up to 9.5×10^{10} ergs per gm.(C). Their radiation stability is a function of the curing system and diluent used. Increased radiation resistance is being developed by use of epoxy-phenolic systems (35, 36). A complete discussion of the effects of the space environment on plastics with an annotated bibliography has been presented by Landrock (37).

STRESS VARIABLES

When a resin is cured around a glass reinforcement, there is a tension set up between the resin and the glass. Various experiments are

being devised to measure this tension and to note how it changes with time and temperature. It has been determined that it does diminish with time, and this it is linearly dependent on the highest temperature to which the resin has been subjected during cure (38). Experiments show that for epoxy-glass composites, the optimum cure temperature is 350°F.

It is assumed that prestressing of a laminate, particularly above the proportional limit, opens small fissures within the laminate, permitting moisture or other contaminates to enter. Similarly, an increase of tension between the resin and glass may also accelerate the opening of the fissures. Recent tests show that preloading of samples has little effect on its environmental resistance. There are also indications that the internal stresses between the resin and glass have only slight influence as far as the environmental resistance of the laminate is concerned.

Stress Concentrations

A glass fiber has an elastic strain up to its ultimate stress with practically no plastic strain. This condition results in the glass being sensitive failure because of stress concentration arising from the unrelieved stress built up by lack of plastic yielding. Thus it is necessary to give special attention to design details, to prevent stress concentration (39).

When designing structures, an accurate analysis must be made to insure not only compatibility of stresses but also of deflections. Gradual changes of sectional thicknesses by adequate tapering or scarf type joints become necessary. By this technique, it is feasible to wind nozzles with the cylinder and protective skirts as a single unitary structure.

Joints in glass reinforced plastics are a problem, because they are associated with stress concentration. However, both bonded and mechanical joints are possible. In bonded joints, scarfing is used to prevent stress concentration. The bond may be plastic to plastic or plastic to metal. Where mechanical joints are involved, such as nozzles, it is desirable to introduce some ductile metal which can relieve stress build-up by yielding. Generally two types of mechanical joints are used. In one type, metal is held in place by the pressure exerted during the glass winding operation around the metal. In the case of the nozzle joint, the metal collar acts like an annular plate. It does not take up membrane stresses. The second type of joint involves bonding the metal and glass during the wrapping operation.

The metal is subjected to membrane stresses, and thus it is designed as a membrane. This particular type of construction results in a lower-weight unit. The metal can be scalloped so as to affect a gradual transition from the large deflection of the glass with its low modulus to a smaller deflection of the metal with its higher modulus.

It is generally not desirable to bolt fittings to glass reinforced plastics. When bolts are required for attaching adjacent sections, however, the plastic area has to be strengthened. This can be accomplished by supplying extra reinforced composite material.

Fatigue Properties

Limited fatigue tests have been conducted on glass reinforced plastics using No. 181 glass fabric (40). Data were obtained from room temperature up to 500°F. Flat specimens were subjected to axial loading. Stress was applied at a frequency of 900 cycles per minute. The fatigue strength of epoxy laminates at zero-mean stress is higher than other resin systems generally used in filament winding. This is expected since fatigue strength at zero-mean stress is influenced by both the tensile and compressive strength of the material (41). Compressive strength of epoxy laminates is higher than other resin systems such as polyester. When laminates are tested parallel to the warp direction of the fabric, the endurance limit is apparently not reached at 10^7 cycles. When tested at an angle to the warp, the fatigue characteristics are quite different and the endurance limit may be reached at 45-degree loadings. This trend theoretically indicates that for stress-balanced reinforced plastics such as filament-wound structures, higher fatigue-strength endurance can be expected (42). Fatigue life of spherical glass-epoxy pressure vessels is shown in Table 6.5.

GENERAL SUMMARY

In general, a designer and fabricator should base his allowable stresses on realistic values, which can be achieved by the particular filament winder and from the specific reinforcement-matrix system. This means that careful operational techniques and precise quality controls must be effective to prevent loss in strength and reduction in other physical properties. Even under the best conditions, some deterioration in properties is expected (43). Care must also be exercised to see that the individual winding equipment does not cause damage to the reinforcement or to the matrix. This necessity of careful attention to all details from choice of material system through

Tabl 6.5 Fatigue Lif f Spherical Glass-Ep xy Pressure Vessels *

Number of Pressure Cycles	Per c nt of Ultimate Strength
10	83
10^2	70
10^3	57
10^4	44
10^5	31
10^6	19

* Kidde cycle rate of 2 to 4 cycles/minute; room temperature and ambient humidity; specimen size is 300 cubic inches (20).

System	Cylinder wall construction	Structual material density, lb./in.^{3}	Cylinder thickness, in.	Cylinder length, in.	Motor case weight, exclusive of insulation and liner, lb.
A1	Steel alloy (modified AMS-6434)	0.283	0.220	102	1904
A2	Steel alloy (modified AMS-6434)	0.283	0.189	134	1706
A3	Glass-filament-wound composite (X-994 glass)	0.072	0.320	137	968

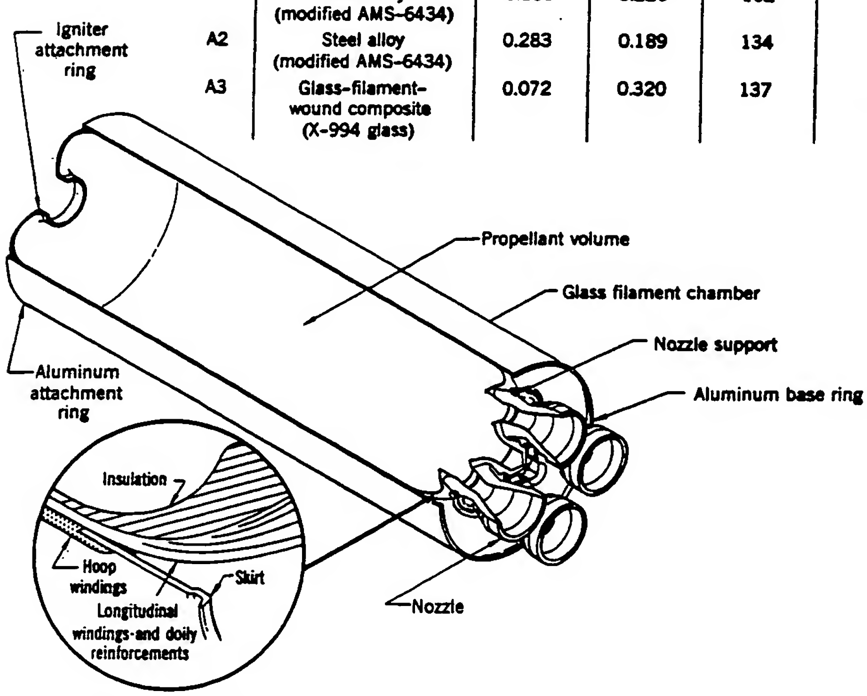


Figure 6.8 Interface attachment design in Polaris A3 First Stage. (Courtesy of Lockheed Aircraft Corp.)

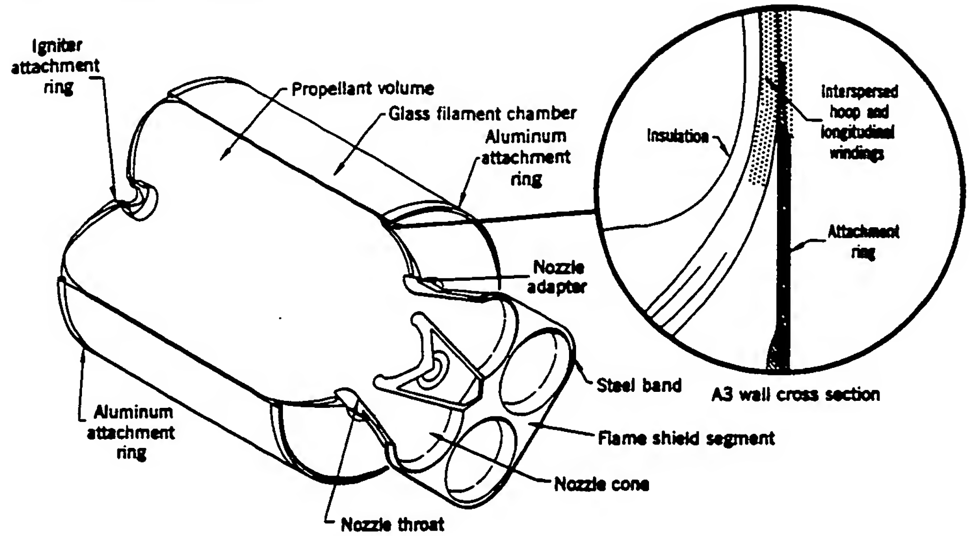
processing and testing to final assembly and application is most important if the full advantages of filament winding are to be achieved.

Specifically, the question is often raised as to the safety factor or ratio of the ultimate strength of the material to the allowable working stress (44). This is difficult to determine since the "standard" strength values of filament-wound structures are so absolutely dependent on the many factors discussed herein. As general practice, the safety factor should be based on the following: (1) accuracy of the estimated stresses on the structure, realizing that a precise load value permits a lower safety factor; (2) degree of precision possible in analysis and determination of stresses; (3) degree of homogeneity and uniformity provided by fabrication techniques and quality control procedures; (4) nature of stress or load, that is, certain types of load, such as long-time impact loading and reverse cycling reduce the allowable design stress of the system; and (5) service requirements, that is, when failure causes personal injury, damage to expensive equipment, or loss of mission and/or production.

Certain theories have been advanced for predicting the service life of reinforced plastics and/or filament-wound structures. Outwater and Seibert (45) assume that the rate of propagation of a microcrack in a glass reinforcing fiber varies with s^n, where s is the glass stress and n for E-glass is about 25. The strength of the reinforcement is proportional to this power function. The ultimate strength of a filament-wound pressure vessel decreases linearly with the time at a given load, and the time to failure of the vessel at a given load increases logarithmically. So the life of a vessel can be predicted at one load after it has been held for a given time at another load. Raphael (46) feels that the service life of plastics can be predicted by an accelerated aging test, based on temperature as the sole accelerated means, using an Arrhenius plot. The relationship between temperature and time to failure provides a straight-line plot which on extrapolation gives time to failure at normal operating temperatures. Experimental data were developed to show the validity of the Arrhenius plot.

Specifications and standards as regards plastic laminates are many and are widely distributed by many agencies and technical societies. Plastec (47) has summarized these in a "Guide to Specifications for Rigid Laminated Plastics." Some of these are of great value to any one concerned with the factors affecting properties of filament-wound structures.

Finally, the feasibility of increased use of the filament-winding technique for both military and industrial structures depends on the



System	Cylinder wall construction	Structual material density, lb./in.^{3}	Cylinder thickness, in.	Cylinder length, in.	Total motor case weight, exclusive of insulation and liner, lb.
A1	Steel alloy (modified AMS-6434)	0.283	0.089	36	524
A2	Glass-filament-wound composite (E-glass)	0.072	0.180	36	382
A3	Glass-filament-wound composite (X-994 glass)	0.072	0.140	42	213

Figure 6.9 Interface attachment design in Polaris A3 Second Stage. (Courtesy of Lockheed Aircraft Corp.)

acceptance of standards, the recognition of the factors important to the properties obtainable, the knowledge of allowable working stresses based on careful fabrication techniques and on close quality control, and on the engineering skill and imagination of the designer and producer. Assuming optimization of all these, one can project filament-wound structures of strengths on the order of 700,000 psi (48).

References

1. H. A. Perry, "Symposium on Standards for Filament-Wound Reinforced Plastics," pp. 1–2, ASTM Special Technical Publication 327, American Society for Testing and Materials, Philadelphia (June 1962).
2. B. Levenitz, "Merits of Filament Winding for Rocket Motor Design," Narmcö Research and Development Report W. O. 090-031, San Diego (December 1961).
3. D. V. Rosato, *Asbestos*, Reinhold Publishing Corporation, New York (1959).
4. D. V. Rosato, Naval Air Material Center Report AML NAM AE 40008, Part II (1949).

5. D. V. Rosato, Naval Air Material Center Report AML NAM AE 40008, Part III (1949).
6. R. C. Tomashot and E. L. Hamilton, WADC Technical Report 56-208 (1956).
7. P. W. Erickson, I. Silver and H. A. Perry, "Proposed NOL-Ring Test Method for Parallel Glass Roving Reinforced Plastics, Evaluation of Chemical Finishes," NAVORD Report 5680 (1959).
8. H. W. Otto, "Compaction Effects in Glass Fibers," J. Am. Ceram. Soc., **44**, No. 2, 68 (1961).
9. H. W. Otto, "Properties of Glass Fibers at Elevated Temperatures," Sixth Sagamore Ordnance Materials Conference (1959).
10. S. Goldfein, *Modern Plastics*, **33**, No. 8, 151 (1956).
11. K. H. Boller, U.S. Forest Products Laboratory, Report No. 1863, Madison, Wisconsin (1957).
12. W. N. Findley, National Advisory Committee for Aeronautics, Technical Note No. 3414 (1956).
13. R. H. Farbes and N. Bryon, WADC Technical Report No. 54-273 (1954).
14. P. D. Covington and S. Oglesby, WADC Technical Report No. 57-10 (1957).
15. D. V. Rosato, *British Plastics*, **33**, No. 8, 348 (1960).
16. Table of Dielectric Materials, Vols. I through VI, Laboratory for Insulation, Massachusetts Institute of Technology, Cambridge, Massachusetts (1951 to 1958).
17. G. R. Rugger and G. U. McNally, SPI Annual Conference Preprints, No. 11A-1 (February 1962).
18. F. Werren and B. G. Heebink, WADC Technical Report No. 55-319 (1955).
19. G. Moore, SPI Annual Conference Preprints, No. 11D-1 (February 1962).
20. F. Wolff and T. Sinta, *Factors Affecting the Performance and Aging of Filament Wound Fiberglass Structures*, Walter Kidde and Company, Inc., New Jersey (August 1961).
21. H. M. Peckam and R. L. Houser, "Compatibility of Materials with Liquid Oxygen," Advances in Cryogenic Engineering, *Proceedings* of the Cryogenic Engineering Conference, Massachusetts Institute of Technology, Cambridge, Massachusetts (September 1958).
22. S. S. Fener and A. F. Torres, *Chemical Engineering*, **70**, No. 15, 168 (1963).
23. "Plastics for Flight Vehicles," Part I Reinforced Plastics, Military Handbook-17, Armed Forces Supply Support Center, Washington (1959).
24. George Epstein and W. Bandaruk, "Crazing in Filament-Wound Pressure Vessels," Aeronutronic Division, Ford Motor Company, Report No. AMTP-5, Newport Beach, California (April 1963).
25. H. E. Martens, Jet Propulsion Laboratory, Progress Report No. 20-289, Pasadena, California (1956).
26. L. O. North, WADC Technical Report No. 54-306, Part I (1954).
27. J. H. Beno, E. F. Smith and A. M. Dowell, *Plastics Technology*, **1** (March 1957).
28. A. J. Dervy, SPI Annual Conference Preprints, No. 7D-1 (February 1962).
29. P. C. Covington and S. Oglesky, WADC Technical Report No. 57-10 (1957).
30. F. R. O'Brien and S. Oglesky, WADC Technical Report No. 54-306 (1955).
31. R. McDonough, "Emissivity of Materials Near Room Temperature," First Symposium on Surface Effects on Space Craft Materials, Jet Propulsion Laboratory, Palo Alto, California (May 12 to 13, 1959).
32. N. E. Wahl and R. R. Lapp, WADD Technical Report No. 60-125 (1960).

33. N. E. Wahl, "Effects of High Vacuum and Ultraviolet Radiation on Reinforced Plastics," *SPE Journal,* **17**, No. 8 (August 1961).
34. J. J. Mione, "Materials in a Nuclear Environment," 25th Annual Meeting of IAS, New York (January 29, 1957).
35. R. E. Bowman, "Radiation Effects," *Materials in Design Engineering,* **50** (July 1960).
36. H. R. Dvorak, "Radiation Effects in Nonmetals," Sagamore Conference, Syracuse University Research Institute, Syracuse, New York (September 16–19, 1958).
37. A. H. Landrock, "Effects of the Space Environment on Plastics: A Summary with Annotated Bibliography," Plastec Report 12, Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, New Jersey (July 1962).
38. J. A. Matta and J. O. Outwater, SPI Annual Conference Preprints, No. 14B-1 (February 1962).
39. F. R. Barnet, Naval Ordnance Laboratory, NAVORD Report No. 2797 (1953).
40. K. H. Boller, U.S. Forest Products Laboratory, Report No. 1863, Madison, Wisconsin (1957).
41. N. Fried, "Fatigue Strength of Reinforced Plastics," SPI Annual Conference Preprints, No. C-3 (February 1962).
42. F. Werren, U.S. Forest Products Laboratory, Report No. 1823-B, Madison, Wisconsin (1956).
43. A. H. Shibley, H. L. Peritt, and Merill Eig, Plastec Report 10, p. 113, Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, New Jersey (May 1962).
44. M. W. Riley, "Low Pressure Reinforced Plastics," Materials in Design Engineering Manual No. 167, p. 110 (February 1960).
45. J. O. Outwater and W. J. Seibert, "On the Strength Degradation of Filament Wound Pressure Vessels Subjected to a History of Loading," NRL Project 62R05 19A Technical Memo No. 196, University of Vermont, Burlington, Vermont (April 1963).
46. T. Raphael, "Predicting the Service Life of Plastics," Paper Presented at Eastern New England Section, Society of Plastics Engineers, Inc. (27 March 1962).
47. "Plastic Laminates: Specifications and Standards," *Materials in Design Engineering,* **58**, No. 1, 81 (1963).
48. J. B. Rittenhouse, W. G. Turevic, and E. E. Morris, "Motor Cases for Large Solid-Propellant Boosters for Spacecraft," SAMPE *Newsletter,* **3**, No. 3, 18 (1963).

7 Design Criteria

GEOMETRICS

Filament-wound structures have been developed having the highest strength-to-weight ratio of any known structural material. Design parameters have been developed based on experimental and production units. The design criterion is concerned with fiber orientation. The basic design method is to orient the fibers in the direction of the principal stresses and proportion the number of fibers with respect to the size of the principal stresses.

In structures where it is geometrically impossible to orient the fibers precisely in the direction of the principal stress they are oriented at some angle with it. A balanced structure can be achieved by proportionately locating fibers at two basically different winding angles (low helicals and circumferentials). The balanced structure is one in which the fibers oriented in any direction in the structure have equal stress applied to them under load.

The ultimate stress of the structure can be calculated using a fiber tensile stress of approximately 370,000 psi (HTS glass) (1). The composite density of the finished laminar structure is in the range of 0.07 pound per cubic inch. The resultant strength-to-weight ratio can exceed 2×10^6 inch. The major past designs have been related mainly to internal pressure systems. Underwater research has now also added major industry study efforts in applying filament-wound structures in shallow and deeply submerged systems.

Filament reinforced plastics differ from most materials of construction in that they combine two essentially different materials, that is, fibers made of glass or metal and synthetic resins. An analogous material is reinforced concrete.

In the analysis of reinforced plastics, it is necessary to assume that the two materials strain equally. In so doing certain other assumptions must be considered.

The assumption is made that a good bond exists between the fibers and the resin so that the tensile and compressive deformations are identical. The shear stresses developed in the bond are relatively low. It must also be assumed that the structure obeys Hooke's law—stress is proportional to strain.

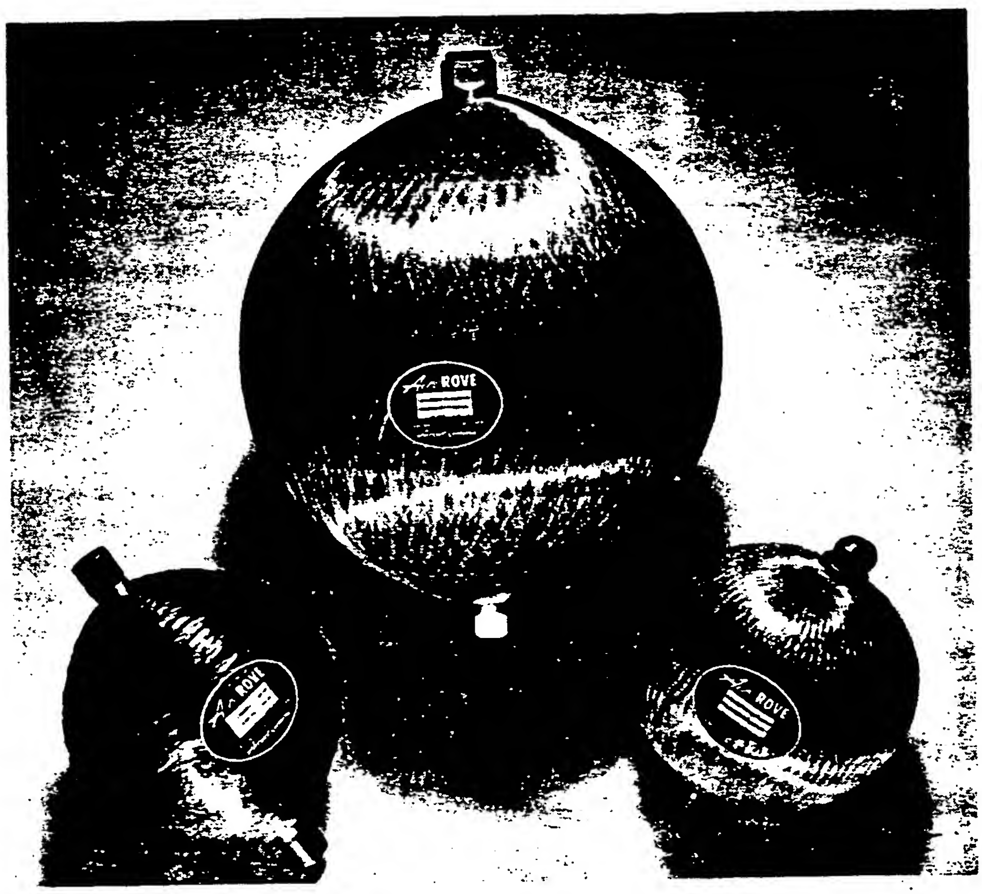


Figure 7.1 Filament-wound spherical pressure vessels. (Courtesy of Aerojet-General Corp.)

Table 7.1 Physical Properties f Reinforced Plastics and M tal Tanks *

	"Poxyglas"	Plain Carbon Steel	Heat-Treated Alloy Steel	Aluminum
Density, pounds/cubic inch	0.072	0.283	0.283	0.097
Tensile strength		40,000	240,000	80,000
Unidirectional, psi	200,000			
Composite, psi	130,000			
Modulus of elasticity, $\times 10^6$, psi	3–6	30	30	10
Thermal coefficient of expansion, inches/inches/°F	5–6	6	6	13
Thermal conductivity, Btu/hour/°F/square feet/inches	2.5	314	314	1416
Strength to density ratio	1,808,000	138,000	828,000	825,000

* Black, Sivalls and Bryson data March 1963 with "Poxyglas," the filament-wound composite plastic, having a compressive strength of 70,000 psi, bearing strength of 35,000 psi and dielectric strength of 365 to 380 volts/mil.

Empirically this proportionality is essentially true for the glass filaments, in that they behave almost elastically up to the rupture point. The resin binders, however, are plastic materials and behave in a partially plastic and partially elastic manner. Typical filament-wound data are shown in Table 7.1, where they are compared to metal tanks.

Classification of Structures

Structures of pressure vessels can be classified in three main groups according to their method of functioning in service.

Pressure Bottle. This group is made up of the conventional type of accumulator or storage type of vessel where the fluid (gas or liquid) is stored under pressure. The fluid is released in order to operate oxygen breathing apparatus, pneumatic or hydraulic servo control systems, burners, etc.

Rocket Motor. This group can be referred to as pressure fluid generators. In such a unit the pressure fluid is produced within the structure either as the product of combustion or as the result of a chemical action between materials already contained in the unit. This group can be used for missile propulsion, operating servo systems. APU generators, etc.

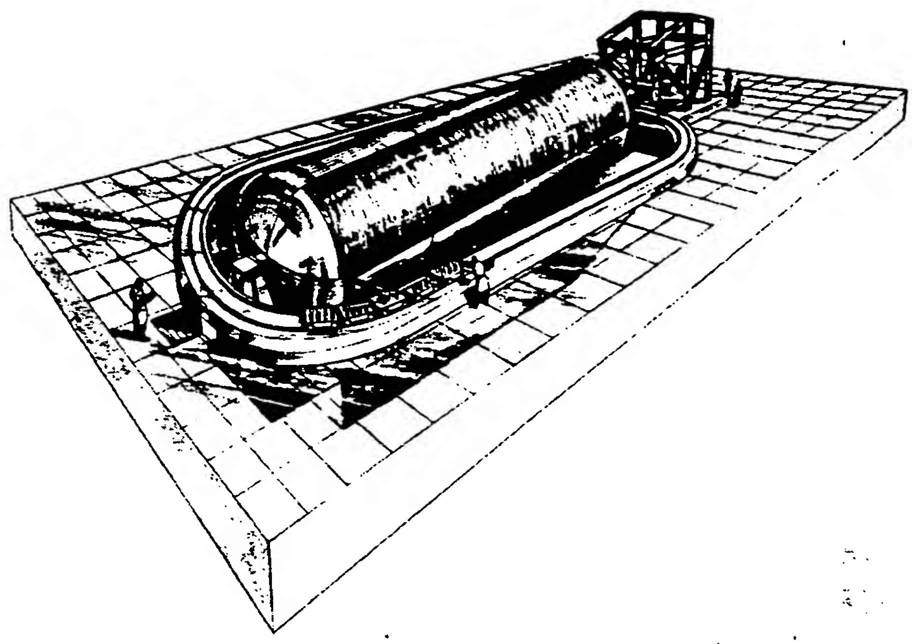


Figure 7.2 An artist's conception shows the fabrication of a giant fiber reinforced plastic solid rocket motor case, 260 inches in diameter and 54 feet long. A case this size would contain approximately 56 million miles of glass thread. Two such rocket motor cases are being built for the Air Force by Aerojet-General Corporation's Structural Materials Division at Todd Shipyards Corp., Los Angeles Division, San Pedro, California. (Courtesy of Aerojet-General Corp.)

Pipe. This group is made up of the most commonly known structures —those used for conducting fluid.

When the more conventional metallic materials are used, the spherical shape produces a more efficient structure than the cylindrical; for a given pressure and volume, it can be shown that a savings in weight or material cost of approximately 25 per cent can be achieved. This condition exists because the metallic materials used are normally isotropic, that is, they have the same properties in all directions, parallel in the plane of the flat panel. In a sphere, the stresses in the wall are the same in all directions. In the case of a cylinder, however, the stress in the hoop direction at right angles to the cylinder axis is twice that in the longitudinal direction along the axis. Since the isotropic material is capable of realizing equal stresses in any direction, it can be determined that the potential strength of the material in the longitudinal direction is not fully utilized.

Reinforced plastics are not isotropic; they are highly directional (orthotropic). This property makes filament-wound units particularly adaptable to structures in which a high degree of orientation is desirable. In using these materials for a sphere, the fibers theoretically require orientation to give uniform strength in all directions. Since fiber orientation can be controlled, a cylindrical filament-wound structure can become approximately as efficient as the spherical shape.

When comparing the weights of various steel and plastic pressure vessels for a given pressure and volume, it is determined that the optimum shape for maximum efficiency of the plastic component is a cylinder of small diameter and considerable length. The reason is that, although it is a relatively simple matter to produce a highly efficient wall parallel to the cylinder, closing the ends is a considerable problem. Extensive research and development has served to improve the efficiency obtainable in cylinders of relatively large diameter and short length.

In many applications, factors such as space, externally applied

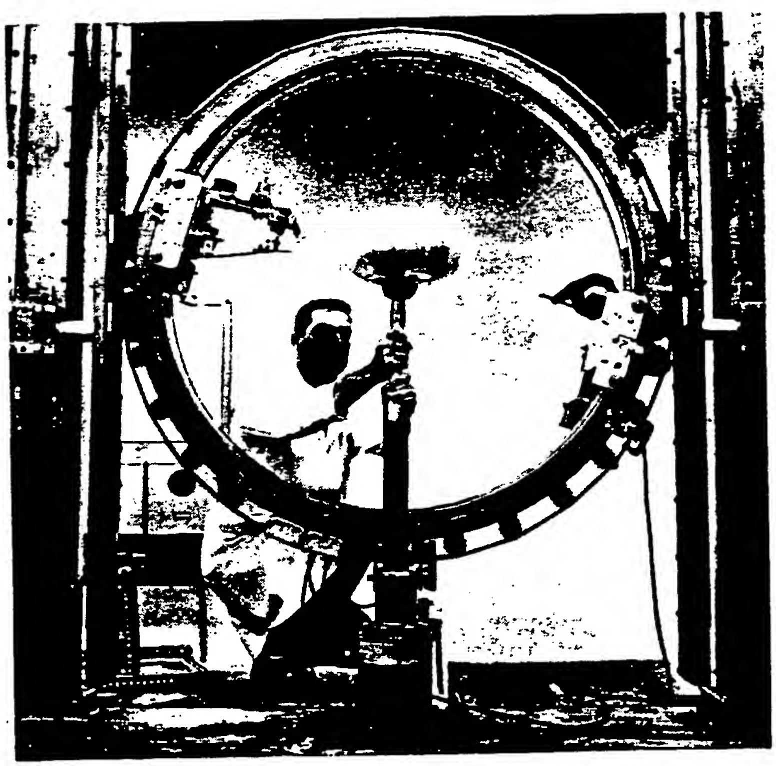


Figure 7.3 Fabrication setup of experimental rocket case for NASA using universal winder. (Courtesy of Narmco Research and Development.)

loads, and manufacturing difficulties have to be taken into account when designing filament-wound structures. Unfortunately, these conditions do not permit utilization of the maximum efficiency of the basic material.

Effect of Fiber Geometry on Strength

Various investigators have developed mathematical means for determining the composite efficiency of glass fiber reinforced plastics (2, 3). In order to analyze the effect of fiber geometry on composite strength, the fundamental mechanics of composite theory is reviewed. Relationships have been derived to relate the load distribution in a composite to the properties of the individual materials. The derivations are based on the following assumptions:

1. Stress is proportional to the strain in both materials.
2. The resin-to-fiber bond is efficient, so that resin and fiber are strained an equal amount under load.
3. The fibers are straight, continuous, and aligned with the axis of the applied load.
4. The material components are isotropic and homogeneous.

Nomenclature

A_c	Area of composite, inches^2
A_{ft}	Total fiber area, inches^2
A_f	Area of fiber in load direction, inches^2
A_m	Area of matrix, inches^2
D	Fiber diameter, inches
E_c	Modulus of elasticity of composite, psi (tension)
E_f	Modulus of elasticity of fiber, psi (tension)
E_m	Modulus of elasticity of matrix, psi (tension)
F_f	Base strength of the fiber, psi
F_m	Base strength of the matrix, psi
F_c	Theoretical composite strength, psi
h	Height of shear plane, inches
L_s	Length of shear plane and required overlap of fibers
P_c	Load of composite, pounds
P_f	Load on fiber, pounds
P_m	Load on matrix, pounds
s_c	Unit stress in composite, psi
s_f	Unit stress in fiber, psi
s_m	Unit stress in matrix, psi
e_c	Unit strain of composite, inches/inches

e_f Unit strain of fiber, inches/inches
e_m Unit strain of matrix, inches/inches

Derivati n

The derivations are as follows:

$$s = Ee \tag{1}$$

where E is the proportionality constant or the modulus of elasticity. For the composite material,

$$s_c = E_c e_c \tag{2}$$

and the stress in the fiber and matrix is

$$s_f = E_f e_f \tag{3}$$

$$s_m = E_m e_m \tag{4}$$

By assumption,

$$e_f = e_c = e_m \tag{5}$$

Thus, Equations (3) and (4) can be written as

$$s_f = E_f e_c \tag{6}$$

$$s_f = E_m e_c \tag{7}$$

Since the load is equal to unit stress times area, the load on the fiber is

$$P_f = s_f A_f = E_f e_c A_f \tag{8}$$

and the load on the matrix is

$$P_m = s_m A_m = E_m e_c A_m \tag{9}$$

The load applied to the composite, P_c, is resisted by the resisting loads in the fiber and matrix; and therefore,

$$P_c = P_f + P_m \tag{10}$$

The ratio of the load carried by the fibers to the applied load is

$$\frac{P_f}{P_c} = \frac{P_f}{P_f + P_m} \tag{11}$$

and substituting for P_f and P_m

$$\frac{P_f}{P_c} = \frac{E_f A_f}{E_f A_f + E_m A_m} \tag{12}$$

Equation (12) can be further simplified by assuming the composite to have an area of one square inch. Thus

$$A_f + A_m = A_c = 1 \tag{13}$$

Equation (12) can now be written as

$$\frac{P_f}{P_c} = \frac{1}{1 + \dfrac{E_m}{E_f}\left(\dfrac{1}{A_f} - 1\right)} \tag{14}$$

The ratio of fiber stress to composite stress can be determined by dividing the fiber and composite loads by their respective area, thus

$$\frac{s_f}{s_c} = \frac{P_f/A_f}{P_c/A_c} = \frac{A_c}{A_f}\,\frac{E_f A_f}{E_f A_f + E_m(1 - A_f)} \tag{15}$$

and since $A_c = 1$,

$$\frac{s_f}{s_c} = \frac{1}{A_f + \dfrac{E_m}{E_f}(1 - A_f)} \tag{16}$$

It can be concluded from Equation (14) that the percentage of the applied load carried by the fiber is a function of the relative moduli of matrix and fiber and also a function of the area fiber resisting the applied load. The same statement is true for the ratio of the stress and the fibers to the stress in the composite. By Equation (16), it is determined that the stress in the fiber increases as E_m/E_f decreases and A_f decreases.

Continuous fibers, such as those in filament winding, cross laminates, and cloth laminates, can transmit the applied load or stress from the point of application to the reaction via a continuous load path. If the fibers are not continuous between the load and the reaction, the matrix must transfer the load from one fiber to the next at the points of discontinuity. Fiber continuity also affects the type of failure of the composite.

With continuous fibers, it can be assumed that the failure will ultimately occur by fracture of the fibers. Discontinuous fibers, on the other hand, can have three other types of failures: (1) fracture of the resin at a weak net section; (2) shear failure in the matrix at the points of discontinuity of the fiber; and (3) failure of the bond between the fibers and the matrix.

The theoretical composite strength is defined as the sum of the strengths of the fiber and matrix materials. This can be written as

$$P_c = A_{ft}F_f + A_mF_m$$

or

$$F_c = A_{ft}F_f + A_mF_m \qquad (17)$$

(where A_{ft} and A_m are part of a unit area) when the composite is assumed to have a unit area.

The composite efficiency is the ratio of the composite strength as tested to the simple composite theoretical strength expressed in per cent. Thus,

$$\text{composite efficiency} = \frac{\text{test strength of the composite}}{\text{theoretical composite strength}} \times 100 \qquad (18)$$

The effective fiber stress can be determined from the load in the fiber and the fiber area. The percentage of the applied load which is carried by the fiber is dependent on E_m/E_f and A_f. This load divided by the fiber area is the effective fiber stress. Thus,

$$s_f\ (\text{effective}) = \frac{P_f}{P_c} \times \frac{\text{test strength composite}}{A_f} \qquad (19)$$

Fiber efficiency can now be defined as the ratio of the developed fiber stress to the base strength of the fibers. Thus,

$$\text{fiber efficiency} = \frac{\text{developed fiber stress}}{\text{basic fiber strength}} \times 100 \qquad (20)$$

Composite efficiency is based on the total glass content plus the total matrix content, and fiber efficiency is based on the glass area oriented in the load direction.

The average tensile strengths of glass fibers in their several common forms are approximately 500,000 psi for a virgin single filament, 400,000 psi for single glass roving, and 250,000 psi for glass strands (as woven into cloth). As a basis for comparing fiber geometrics, the base glass strength will be assumed as 400,000 psi for glass roving. Single glass filaments are not practical to handle, and glass strands which are used in cloth have undergone the first phase of fabrication.

Table 7.2 shows that filament-wound fibers form the most efficient composite, and that composite efficiency is reduced as fiber orientation is changed from unidirectional to random orientation. Note that the most inefficient construction incorporates the use of woven cloth.

Table 7.2 C mp site Efficiency of Reinf rced Plastics (3)

Fiber Orientation	Fiber Length	A_{fT}	A_m	F_{Theo},* psi	F_{Test},† psi	Composite Efficiency ‡
Filament-wound fibers	Continuous	0.77	0.23	310,000	180,000	58.0%
Cross-laminated fibers	Continuous	0.48	0.52	197,000	72,500	36.8%
Cloth-laminated fibers	Continuous	0.48	0.52	197,000	43,000	21.8%
Mat-laminated fibers	Continuous	0.48	0.52	197,000	57,200	29.0%
Chopped-fiber systems	Non-continuous	0.13	0.87	60,700	15,000	24.7%

* $F_{Theoretical} = A_fF_f + A_mF_m$: where E_f = 400,000 psi; F_m = 10,000 psi, with NOL type specimen F is 200,000 psi.

† Typical test data.

‡ Composite efficiency equals test strength of composite/simple theoretical composite strength (see Equation 18).

Glass Content. There is a relationship between the way the glass is arranged and the amount of glass that can be packed in a given object. By placing continuous strands next to each other in a parallel arrangement, more glass can be placed in a given volume. Glass content ranges from 65 to 90 per cent by weight.

When one-half of the strands are placed at right angles to the other half, glass loadings range from 55 to 75 per cent. A random arrangement gives glass content ranging from 15 to 50 per cent. Figure 7.4 shows laminate density versus per cent of E-glass by weight or by volume.

STRESSES

Fundamental Stress Analysis

Cylinder. Consider a cylinder of inside radius r, outside radius R, and length L containing a fluid under pressure p. The circumferential or hoopwise load in the wall (t — thickness) is proportional to the pressure times radius = pr, and the hoop stress

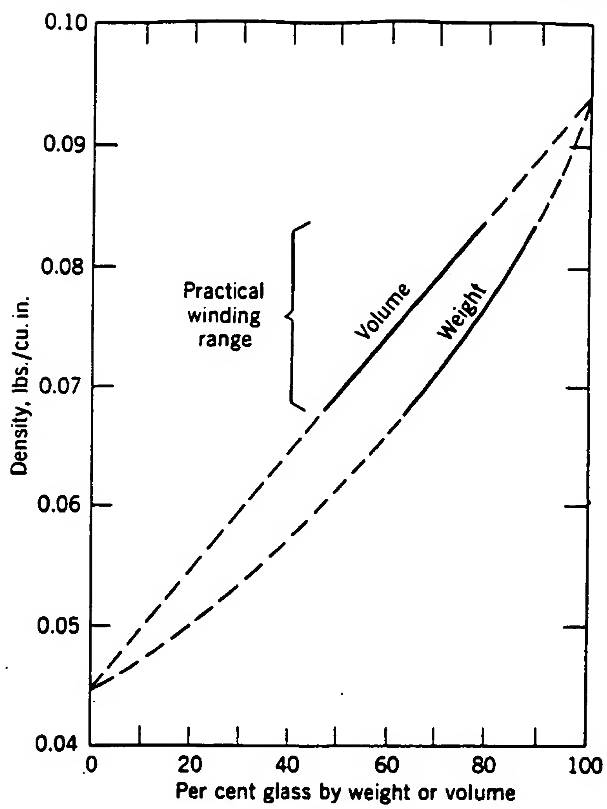


Figure 7.4 Laminate density versus per cent glass by weight or volume.

$$f_h = \frac{\text{hoopwise load}}{\text{cross sectional area}} = \frac{pr}{t} \tag{21}$$

or

$$= \frac{pd}{2t} \tag{22}$$

similarly, the longitudinal stress

$$f_l = \frac{pd}{4t} \tag{23}$$

(assuming $\pi(R^2 - r^2) = 2\pi rt$ for a thin-walled tube).

This condition of the hoop stress being twice the longitudinal stress is normal for a cylinder under internal pressure forces only. The load in pounds acts on the tube at a distance from one end and a bending

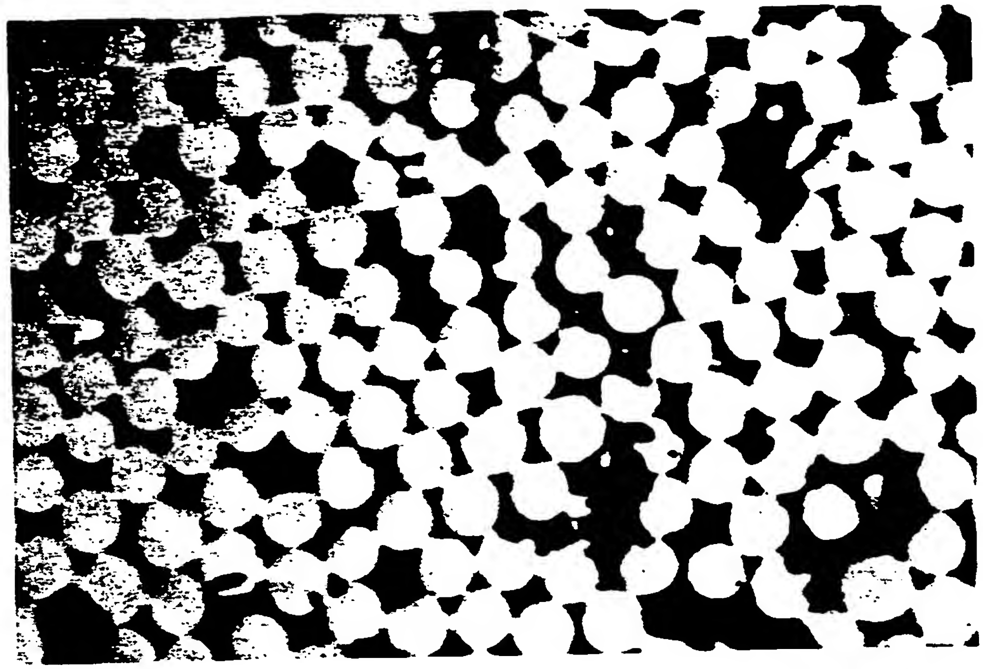


Figure 7.5 Cross section photomicrograph of fiber edge. (Courtesy of NAA, Rocketdyne.)

moment M is introduced. This produces a bending stress in the wall of the cylinder of

$$f_b = \frac{My}{I}, \tag{24}$$

where $y = R$ and I = the moment of inertia. For a cylinder

$$I = \pi \frac{(D^4 - d^4)}{64} \text{ in.}^4 \tag{25}$$

This stress must then be considered in addition to the longitudinal stress already present because of internal pressure.

If the end closures are in the form of flat plates, bending stresses due to the internal pressure are introduced as

$$F_b = 1.25 \frac{pr^2}{t_l} \tag{26}$$

where t_l = thickness of end.

This necessitates the wall of a flat disc-type end being extremely

thick compared with a hemispherical end which is found to be the most efficient shape where the stress in the wall is

$$\frac{pd}{4t} \tag{27}$$

Figure 7.6 compares the thicknesses and corresponding volumes of the two types of ends for varying values of r (assuming $p = 2{,}000$ psi and ultimate stress in the wall material of 100,000 psi).

The volume of the flat end is found to be approximately four times the volume of the hemispherical end for any given radius of tube, resulting in increased weight and material cost. Other end shapes such as an ellipse will have a volume or weight somewhere between the two, depending on the actual shape chosen.

Sphere. The circumferential load in the wall of the sphere under internal pressure is equal to the pressure times the internal cross-sec-

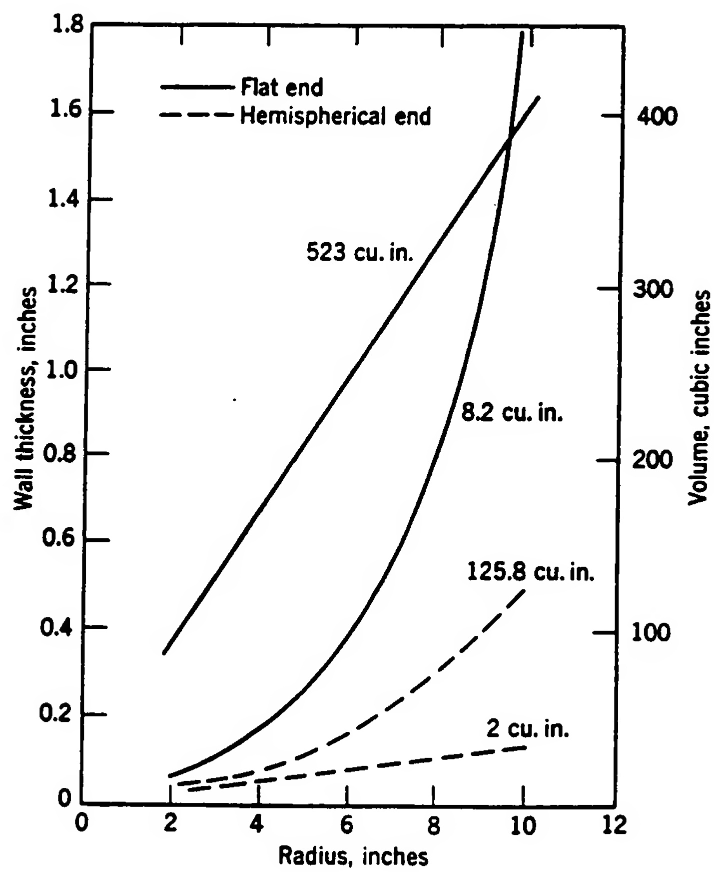


Figure 7.6 Comparison of thickness and volume for a flat end and a hemispherical end: assuming pressure of 2,000 psi and ultimate stress of material at 100,000 psi.

tional area, and the hoop stress, using the previous assumption, is found to be

$$f_h = \frac{pd}{4t} \tag{28}$$

It will readily be seen that no matter which section is chosen, provided the plane of the section passes through the center of the sphere, the condition will be the same, and it can be said that the hoop stress will be the same in all directions (4).

When it is assumed that

$$\pi(R^2 - r^2) = 2\pi rt \tag{29}$$

it is determined that for wall thicknesses up to approximately 3 inches, the error is negligible. It can also be determined that the per cent of error decreases as the ratio r/t increases. Table 7.3 provides size versus weight of spheres.

Fiber Orientation. For a sphere with the stresses uniform in all directions, it follows that the fibers require equal orientation in all directions. The problem of orientation resolves itself purely into one of practical application of the fibers.

Table 7.3 *Data For 3,000 psi Fiber Glass Spheres (5)*

Capacity, cubic inches	Outside Diameter, inches	Nominal Weight, pounds	Maximum Weight, pounds	Overall Length, inches
50	$5\frac{1}{4}$	1.50	1.60	$5\frac{5}{8}$
100	$6\frac{1}{2}$	2.50	2.63	$6\frac{15}{16}$
200	$8\frac{1}{8}$	4.44	4.62	$8\frac{1}{2}$
300	$9\frac{1}{4}$	6.25	6.56	$9\frac{5}{8}$
400	$10\frac{1}{8}$	8.06	8.48	$10\frac{9}{16}$
500	$10\frac{15}{16}$	9.87	10.35	$11\frac{5}{16}$
650	$11\frac{15}{16}$	12.56	13.18	$12\frac{5}{16}$
880	$13\frac{1}{16}$	16.00	16.80	$13\frac{3}{8}$
1,070	14	20.06	21.07	$14\frac{3}{8}$
1,325	$15\frac{1}{8}$	24.50	25.73	$15\frac{7}{16}$
1,575	$15\frac{7}{8}$	28.75	30.15	$16\frac{1}{4}$
1,800	$16\frac{5}{8}$	32.75	34.42	$16\frac{15}{16}$
2,500	$18\frac{1}{2}$	44.81	47.06	$18\frac{7}{8}$
3,200	20	56.50	59.32	$20\frac{7}{16}$

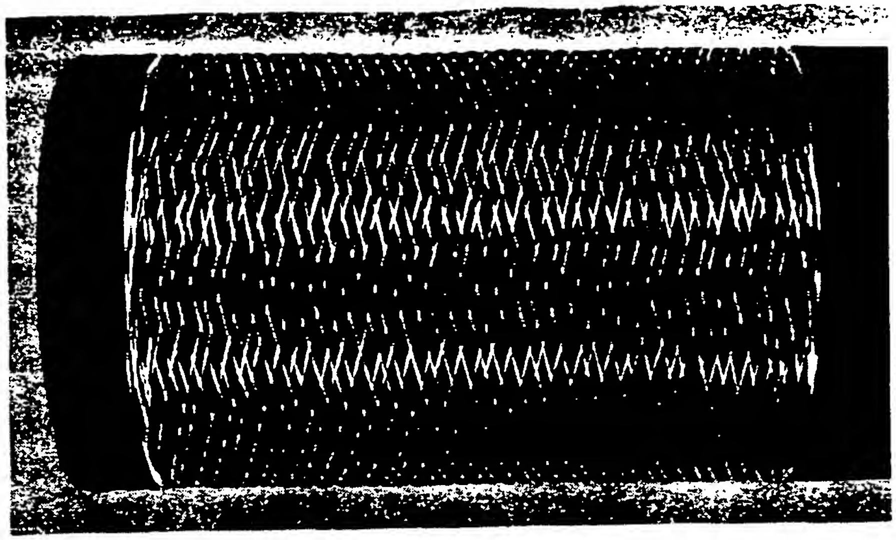


Figure 7.7 Fiber pattern for cylindrical shape. (Courtesy of Narmco Research and Development.)

In the cylinder, the fibers are specifically oriented to meet any condition of stressing. The simplest method of doing this is to employ a single helical pattern.

Theory shows that this is highly sensitive to variations in the longitudinal hoop-stress ratio and also to the accuracy of the angle wound. The addition of pure hoop windings to the helix gives a theoretical gain in stability with no loss of strength or efficiency. In order to develop the most satisfactory orientation, the winding is performed so that two different helix angles are used.

Simplified Envelope Efficiency (6, 7)

The following derivation is based on requirements for an internal pressure vessel. Symbols are identified as follows:

R	radius of basic shape
T	wall thickness
A	surface area
V	volume
α	helix angle (to axis)
S	(based on netting theory) fiber stress
P	pressure
L	length of ovaloid curve

The ratio TA/V (Equation 30) is a valid measure of envelope efficiency providing material density is constant. For simplicity the

investigator assumed that the wall thickness is very small in relation to the radius. The filament-wound sphere is constructed according to a pattern which will provide equal strength in any direction along its surface. Such a pattern would comprise a large number of circles uniformly distributed with respect to direction. Consider a local area on the sphere as projected on the tangent plane and the strength component of all families of parallel filaments (normal to a given base line). The following relationship can be shown to be true

$$\frac{\Sigma \sin^2 \alpha}{N} = 0.5 \tag{31}$$

where N = the number of filaments.

The strength of the spherical shell equals $0.5S$. The envelope efficiency is

$$T = \frac{PR}{2(0.5S)} = \frac{PR}{S} \tag{32}$$

$$V = \tfrac{4}{3}\pi R^3 \tag{33}$$

$$A = 4\pi R^2 \tag{34}$$

$$\frac{TA}{V} = \frac{PR4\pi R^2}{S\frac{4}{3}\pi R^3} = \frac{3P}{S} \quad \text{(Sphere)} \tag{35}$$

In considering the cylindrical portion of a chamber with ovaloid ends an easy winding pattern to analyze consists of circular and longitudinal windings only. Since the girth loading is twice the longitudinal loading,

$$\text{The girth strength} = \frac{2S}{3} \tag{36}$$

Its envelope efficiency is

$$T = \frac{PR}{2S/3} = \frac{3PR}{2S} \tag{37}$$

$$A = 2\pi RL \tag{38}$$

$$V = \pi R^2 L \tag{39}$$

$$\frac{TA}{V} = \frac{3PR2\pi RL}{2S\pi R^2 L} = \frac{3P}{S} \quad \text{(Cylinder)} \tag{40}$$

Any other netting pattern for the cylindrical shell will yield the same results if the girth to longitudinal strength ratio remains two to one. For example, in a simple helical system wherein

$$\alpha = 54\tfrac{3}{4}° \tag{41}$$

$$\tan \alpha = \sqrt{2} \tag{42}$$

$$\sin \alpha = \frac{\sqrt{2}}{\sqrt{3}} \tag{43}$$

$$\text{Girth strength} = S \sin^2 \alpha = \tfrac{2}{3}S \tag{44}$$

The ovaloid end is a shape which does not lend itself readily to computation of the volume and surface area. Also, for simplifying this analysis a specific ovaloid was selected which would have no polar opening and in which every fiber lies in a radial plane. An expression is given for the volume of this ovaloid (8):

$$V = 1.37674R^3 \tag{45}$$

An expression for the surface area had not been developed; also, the wall thickness increases at the pole as every fiber crosses that area. Coordinates can be developed for the profile, however, and these have been numerically integrated to yield the approximate length of this ovaloid profile from the cylinder tangency to the polar axis:

$$L_0 = 1.314R \tag{46}$$

This particular ovaloid end will be formed by the continuation of the longitudinal fibers of the straight cylinder described above. These comprise one third of the cylinder wall, or

$$T = \frac{PR}{2S} \tag{47}$$

And the structural volume will be

$$TA = \frac{2\pi R^2 P}{2S} 1.314R \tag{48}$$

$$\frac{TA}{V} = \frac{2\pi R^2 1.314R}{2S 1.37674R^3} = 2.9984 \frac{P}{S} \tag{49}$$

$$\text{The disagreement} = \frac{3 - 2.9984}{3} 100 = 0.053\% \tag{50}$$

With this arithmetic agreement, what has been strongly implied must now be recognized:

$$\left(\frac{TA}{V}\right)_{\text{Sph.}} = \left(\frac{TA}{V}\right)_{\text{Cyl.}} = \left(\frac{TA}{V}\right)_{\text{Ov.}} \tag{51}$$

The inequality of the envelope efficiency for various vessels constructed of homogeneous materials is well-known. In filament-wound structures the cylinder allows near perfect nesting of the filament bands, while the sphere and ovaloid consist of bands converging to an overlap and again diverging. It is, therefore, to be expected as shown in practice that these shapes have a slightly lower glass fiber density and allowable fiber stress. The most efficient structural envelope would therefore seem to be a long cylinder with ovaloid ends.

Actual filament-wound spheres and ovaloids will be comprised of slightly different winding patterns than those analyzed (optimum) to accommodate polar openings. If these are truly balanced, having constant fiber stress throughout, it is probable that they will also have the same efficiency when allowances are made for the required polar plug fittings (9).

These derivations are based on analyzing the composite by the netting theory. Another approach is sometimes referred to as the orthotropic analysis. In the netting theory (as used in these simplified examples) the resin is assumed to have no load-carrying ability, and the stress in each fiber is assumed to be equal and constant. The more complicated method used to predict the behavior of fiber glass under load is the orthotropic analysis.

High-Ratio Analysis (10)

In applications such as recoil-less rifles, a design engineer should consider the dynamic rate sensitivity factor in order to obtain the full potential and maximum efficiency of filament-wound structures. Accurate knowledge of the rate-sensitivity factor will enable engineers to design more efficient structures, in particular where low safety factors or one-time firings are permissible.

Normal slow-rate testing conducted at 0.2 inch per minute on tensile specimens will cause them to fail in 1.5×10^5 milliseconds if it is assumed that failure of the specimen occurs in approximately one-half inch of travel. At 1 millisecond, tensile strength is 70,000 psi. At 1.5×10^5 milliseconds, strength is 37,000 psi. The ratio of these two strengths gives a rate-sensitivity factor of 189 per cent. These values are all based on woven glass fabric. It is expected that a rate-sensitivity factor for unidirectional glass fiber would be much higher. Limited tests on unidirectional glass fibers indicate a rate sensitivity increase of 175 per cent as opposed to the 89 per cent increase for the woven fabric laminate.

DESIGNS

D sign f Winding Patterns

Two basic patterns have been developed and used by industry to produce filament-wound structures, namely, circumferential winding and helical winding. Each winding pattern can be used alone or in various combinations, in order to provide different structures.

Circumferential Winding. This pattern basically involved the circumferential winding at approximately a 90-degree angle with the axis of rotation, interspersed with longitudinal reinforcements.

Maximum strength is obtainable in the hoop direction. This type of pattern generally does not permit winding of slopes over 20 degrees when using a wet winding reinforcement or 30 degrees when using a dry winding process. It also does not result to the most efficient structure when end closures are required. With end closures and/or steep slopes, a combination of helical and circumferential winding is used.

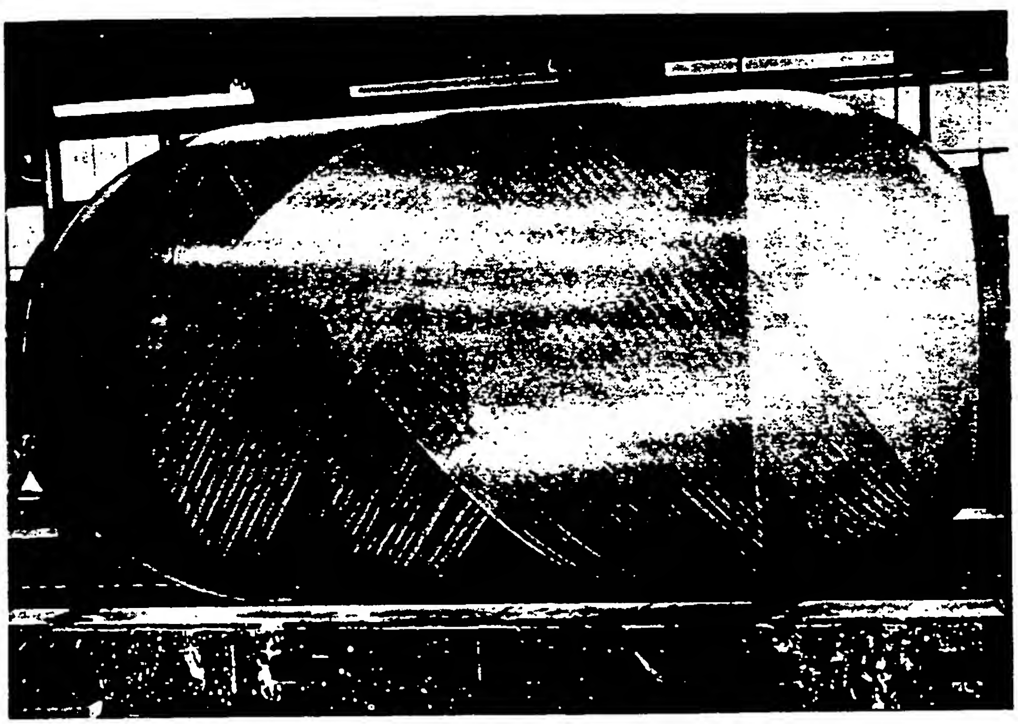


Figure 7.8 Combination of helical and longitudinal windings in 6-foot-diameter vessel. (Courtesy of Boeing Airplane Co.)

Helical Winding. The reinforcements are applied at any angle from 25 to 85 degrees to the axis of rotation. No longitudinal filament need be applied, for low winding angles provide the desired longitudinal strength as well as the hoop strength. By varying the angle of winding, many different ratios of hoop to longitudinal strengths can be obtained.

Two different techniques of applying the reinforcement in helical windings are used by industry. One technique is the application of only one complete helical revolution around the mandrel from end to end. The other technique involves a multicircuit winding procedure, which permits a greater degree of flexibility in angle of wrapping and length of cylinder.

Basic Design Principles for Winding

To develop an efficient high-strength–low-weight filament-wound structure, it is apparent that only continuous reinforced filaments should be used (11). Structural properties are derived primarily from the arrangement of continuous reinforcements in a netting system in which the forces, owing to internal pressure, are resisted only by pure tension in the filaments (applicable to internal-pressure systems).

Closed-End Cylinder. This type of structure provides for a balanced netting of reinforcements. Although the cylinder and the ends require two distinctly different netting systems, they may be integrally fabricated. The structure consists of a system of low helix angle windings carrying the longitudinal forces in the cylinder shell and forming integral end closures which retain their own polar fittings. Circular windings are also applied to this cylindrical portion of the vessel, yielding a balanced netting system. Such a netting arrangement is said to be balanced when the membrane generated contains the appropriate combination of filament orientations to balance exactly the combination of loadings imposed.

The girth load of the cylindrical shell is generally two times the axial load. The helical system is so designed that its longitudinal strength is exactly equal to the pressure requirement. Such a low-angle helical system has a limited girth strength. The circular windings are required in order to carry the balance of the girth load.

The end dome contains no circular windings since the profile is designed to accommodate the netting system generated by the terminal windings of the helical pattern. It is termed an ovaloid; that is, it is

the surface of revolution whose geometry is such that fiber stress is uniform throughout and there is no secondary bending when the entire internal pressure is resisted by the netting system.

The ovaloid netting system is the natural result of the reversal of helical windings over the end of the vessel. The windings become thicker as they converge near the polar fittings. In order to resist internal pressure by constant filament tension only, the radius of curvature must increase in this region. It can also be reasoned that the radius of curvature at the cylinder junction will be equal to one half the cylinder radius when the helix angle $\alpha = 0°$, and equal to the cylinder radius when $\alpha = 45°$. The profile will also be affected by the presence of an external axial force.

In the application of bidirectional patterns, the end domes are still formed by fibers which are laid down in polar winding patterns. The best geometrical shape of the dome is an oblated hemispheroid. Theoretically, the allowable stress level in the two perpendicular directions should be identical. However, the efficiency of the longitudinal fibers is less than that of the circumferential fibers. It is possible to estimate an optimum diameter or length-to-diameter ratio of a cylindrical case for a given volume.

Filament-Wound Sphere. This type of structure provides another example of a balanced netting system. It is simpler in some respects than the closed-end cylinder. The sphere must be constructed by winding large circles omnidirectionally and by uniform distribution over the surface of the sphere. In practice, distribution is limited, so that a small polar zone is left open to accommodate a connecting fitting.

The netting pattern required generates a membrane in which the strength is uniform in all directions. The simplest form of such a membrane would have half of its structural fibers running in one direction and the other half at right angles to this pattern. This layup results in the strength of the spherical membrane being one-half of the strength of a consolidated parallel fiber system (12).

Oblated Spheroid. Practical design parameters have shown that the sphere is the best geometric shape when compared to a cylinder for obtaining the most efficient strength-to-weight pressure vessel. The glass-fiber resin reinforced plastics are the best basic constituents. Certain modifications of the spherical shape can improve the efficiency of the vessel (13). One modification involves designing the winding pattern of the fibers so that unidirectional loading can be maintained.

In this type of structure, it is generally assumed that the fibers are under equal tension. This type of structure is identified as an isotensoid. The geometry of this modified sphere is called oblated spheroid, ovaloid, or ellipsoid.

Isotensoid. The term isotensoid identifies a pressure vessel consisting entirely of filaments that are loaded to identical stress levels. The head shape of an isotensoid is given by an elliptic integral, which can most readily be solved by a computer. Its only parameter is the ratio of central opening to vessel diameter. This ratio determines the variation of the angle of winding for the pressure vessel. During pressurization the vessel is under uniform strain; consequently, no bending stresses or discontinuity stresses are induced.

It is characterized by a short polar axis and a larger perpendicular equatorial diameter. The fibers are oriented in the general direction of a polar axis. Their angle with this axis depends on the size of the pole openings (end closures). Levels of 200,000-psi composite stress in actual rocket cases have been achieved for this shape.

Toroidal (14). In a filament-wound toroidal pressure vessel made with two sets of filaments symmetrically arranged with respect to the meridians, the following two basic requirements must be fulfilled: (1) static equilibrium at each point, which determines the angle between the two filaments, and (2) stability of the filaments on the surface, which requires the filaments to follow geodesic paths on the

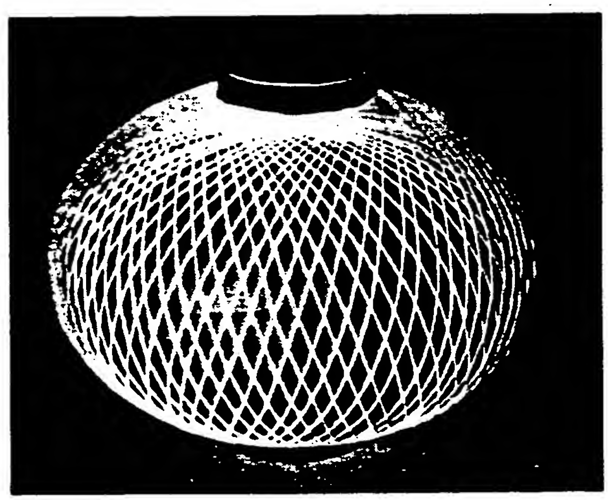


Figure 7.9 Winding pattern for isotensoid configuration. (Courtesy of Narmc Research and Development.)

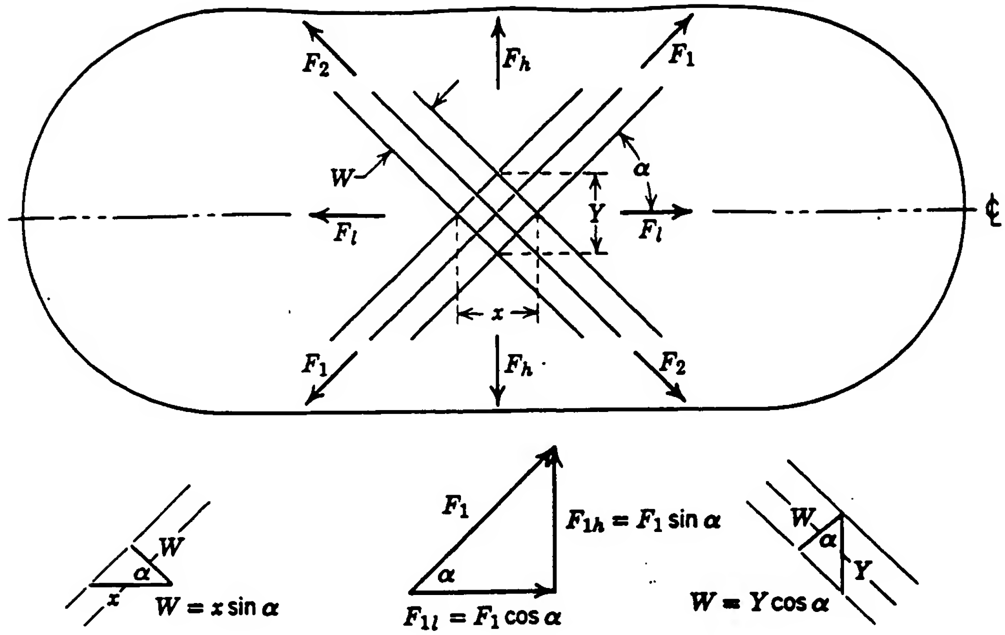


Figure 7.10 Netting analysis of filament-wound cylinder.

surface. When the equation of the surface is given, these two requirements are generally incompatible. One way to reconcile the correct angularity of the filaments (equilibrium) with the correct paths of the filaments (stability) is to take some freedom in determining the geometry of the surface.

Design of Pressure Cylinders

The basic design analysis generally considered for wound vessels subjected to internal pressures takes into consideration the assumptions given earlier in this chapter. As shown in Figure 7.10, the netting analysis using a constant helix angle can put all fiber stresses in tension. In this cylindrical example the forces in the hoop and longitudinal directions can be resolved into a single resultant force in the direction of the fiber. The cross-sectional area can be used to determine the actual fiber stress.

The following information will show that the force in the hoop direction of a cylinder is proportional to $\sin^2 \alpha$. The force in the longitudinal direction is proportional to $\cos^2 \alpha$. When considering a thin-walled cylinder with the hoop stress being twice the longitudinal stress, the theoretical optimum helical angle (α) to produce the most efficient strength-to-weight unit is *54.75 degrees.*

The nomenclature for this design analysis is:

F	Directional force
	F_h (hoop)
	F_l (longitudinal)
α	Helix angle (to axis)
t	Wall thickness
x	Distance axial direction
Y	Distance radial direction
S	Stress
	S_h (hoop)
	S_l (longitudinal)
	S_f (fiber)
W	Width of fiber strand

To determine hoop directional force consider

$$F_h = F_{1h} + F_{2h} \tag{52}$$

$$F_h = 2F \sin \alpha \tag{53}$$

$$S = \frac{F_h}{xt} = \frac{2F}{xt} \sin \alpha \tag{54}$$

$$\frac{S_h}{W} = \frac{2F}{Wxt} \sin \alpha \tag{55}$$

$$\frac{S_h}{W} = \frac{F}{Wx\frac{t}{2}} \sin \alpha \tag{56}$$

since

$$S_f = \frac{F}{W\frac{t}{2}} \tag{57}$$

and

$$W = x \sin \alpha \tag{58}$$

thus

$$\frac{S_h}{x \sin \alpha} = \frac{S_f}{x} \sin \alpha \tag{59}$$

or

$$S_h = S_f \sin^2 \alpha \tag{60}$$

As shown in Figure 7.10, to determine forces in the longitudinal direction the cosine of the helix and the radial direction force are used.

By substituting these symbols for the sine and axial direction force in Equations (52) through (60), the result is

$$S_l = S_f \cos^2 \alpha \tag{61}$$

In a thin-walled cylinder the hoop stress is twice the longitudinal stress. In order to obtain the theoretically maximum strength-to-weight structure, the helix angle can be determined by simultaneously solving equations as follows:

$$\frac{S_h}{S_l} = \frac{\text{Eq. (60)}}{\text{Eq. (61)}} = 2 \tag{62}$$

$$\frac{S_h}{S_l} = \frac{S_f \sin^2 \alpha}{S_f \cos^2 \alpha} = \tan^2 \alpha = 2 \tag{63}$$

or

$$\tan \alpha = \sqrt{2} \tag{64}$$

thus

$$\alpha = 54.75° \tag{65}$$

The validity of the theoretical helix angle derivation has been demonstrated by tests on cylinders wound at an angle 3 degrees more than 54.75 degrees. Under hydrostatic test, there was no increase in the diameter, and all strain resulted in a change in length. The reverse relationship has also been demonstrated. The elastic properties of a balanced cylindrical structure are such that strain is equal in all directions.

Original cylindrical winding design parameters considered the use of 54.75 degrees as the helical winding angle that provided optimum design. As design models evolved and structural tests were conducted, it was determined that in order to fabricate the most efficient cases, different winding patterns had to be used.

These patterns combine low-helix-angle wind to provide the longitudinal reinforcement with higher angle to provide circumferential reinforcement. The low-angle filaments can be continuously built up without crossovers of reinforcements. Low-angle wind forms the basic end dome. High-angle reinforcements are applied at 90 degrees for maximum strength. The actual design pattern to be used, which could also be 54.75 degrees, is dependent on factors such as overall dimensions, types of end enclosures, materials of construction, type of winding machine, and structural load requirements.

A recent development was the design and fabrication of a 13-ft-diameter by 25-foot-long glass-wound chamber. It was designed for

a 1,200 psi minimum burst pressure with a composite hoop stress of 85,000 psi. A combination of low helical and 90-degree windings provided for meeting the required structural loads. Forward and aft integral steel end closures were generated by the helical windings in an elliptical shape. The polar fittings account for 27 per cent of the total weight, which is 20,000 pounds. Approximately 9,600 pounds of glass fiber were used.

A low-carbon steel case of comparable size and based on an assumed minimum tensile strength of 70,000 psi would have a weight equal to approximately five times that of the plastic unit. It would have its ends made separately. Welded end caps and at least one axial weld would be required. The resultant metal-unit cost because of manufacture would be twice the plastic, with tooling cost at least six times more.

Binary and Complex Netting. Structures of this type contain two or more winding systems with each wound at a specific helix angle. There are several valid reasons for winding such structures. The sphere requires many large circles to be uniformly distributed over its surface with respect to both angular deviation from the polar axis and linear spacing along the surface. Such a group of large circles uniformly spaced in a constant angle to the polar axis constitutes one winding system at a given helix angle.

Construction of a pressure cylinder with integral ovaloid end closures requires one system of helical windings at a low angle to form the ends as well as to carry the longitudinal forces in the cylinder. Additional circular windings at nearly a 90-degree helix angle are required to carry the balance of girth load.

Another binary system is similar to the cylindrical portion of the ovaloid end cylinder which may be subjected to compression or bending. The axial forces carried by the low helical system must be balanced by the opposite stress and circular windings. The binary system representing any combination of two helical windings is most commonly employed in pressure cylinders.

Complex netting systems may be treated by methods similar to those used in binary systems. When all systems operate in parallel, the girth strength will be proportional to the sum of the girth strengths for all components.

Simplified Netting Analysis. Design calculations can be made on fiber strand strength alone. In developing this type of approach several assumptions are made.

1. The glass and resin are each homogeneous and elastic.
2. The glass is anisotropic, that is, it has directional properties.
3. The resin acts as an agent for evenly transmitting the stress throughout the filament-wound structure.
4. The strength of the resin is negligible in comparison to the glass strength.
5. The maximum allowable strain of the resin is greater than the maximum strain of the glass fiber. This is in fact a true assumption if the proper resin is used. Use of the proper resin, one with an appreciably lower E than that of glass, insures that failure will occur in the glass rather than in the resin, thus affording maximum efficiency.

A free body diagram of force system acting on the fibers per inch across the fibers is shown in Figure 7.11. Symbols and subscripts are identified as follows (10):

Subscript "hel" refers to helical winding.
Subscript "ho" refers to hoop windings.
F_s = force per strand.
F_{ho} = force per inch in hoop direction.
F_{Ho} = resultant force per inch in hoop direction.
F_L = resultant force per inch in longitudinal direction.
σ_{ho} = stress in the hoop direction.

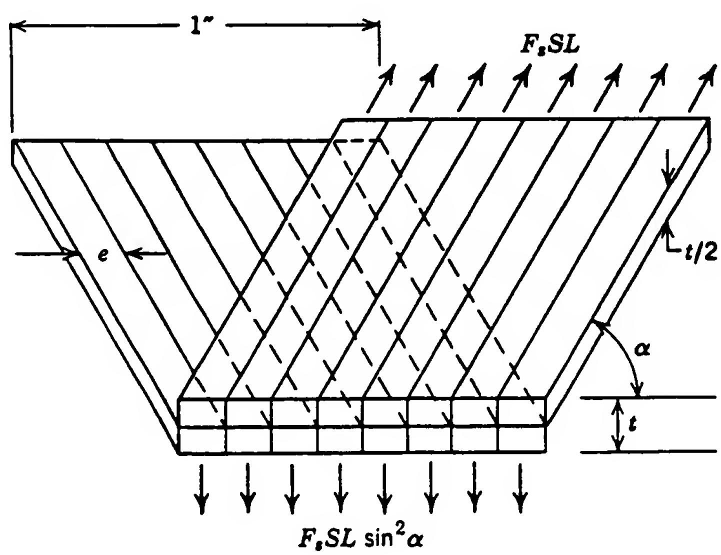


Figure 7.11 Simplified netting analysis: fiber to hoop force relationship per inch across fibers.

σ_L = stress in the longitudinal direction.

S = strands per inch per layer. Since the fibers were tangent to each other, the number of strands per inch per layer in the helix direction equals the number of strands per inch per layer in the hoop direction, that is, $S_{hel} = S_{ho}$.

A = cross-sectional area of the glass fibers.

L = number of layers. Each complete helical coverage consists of two layers, contrasted to one layer for each hoop winding.

e = width of one end.

t = thickness.

α = helical angle of wrap.

The resultant force in the direction of the fiber is given by the product of $F_s S_{hel} L_{hel}$. The component of force in the hoop direction is

$$F_{ho} = \text{force/inch} = F_s S_{hel} L_{hel} \sin^2 \alpha \tag{66}$$

The $\sin^2 \alpha$ is introduced because of the unidirectional property of the glass fibers. The square arises from resolution of area as well as forc in the hoop direction. Similarly, the force in the hoop direction produced by just the hoop windings is

$$F_s S_{ho} L_{ho} \tag{67}$$

The total resultant force in the hoop direction is the superposition of the two forces.

$$F_{Ho} = F_s S_{hel} L_{hel} \sin^2 \alpha + F_s S_{ho} L_{ho} \tag{68}$$

(resin strength is neglected since it is only approx. 3,000 psi).

The resultant force in the longitudinal direction is determined in a similar fashion. It is obvious that the circumferential windings do not contribute to the force in the longitudinal direction. Therefore, the longitudinal force is

$$F_L = F_s A_{hel} L_{hel} \cos^2 \alpha \tag{69}$$

For clarification, it should be noted that when the material is homogeneous, the ratio of hoop and longitudinal stresses in a closed pressure vessel is two to one, as may be seen from the following equations:

$$\left.\begin{aligned} \sigma_{ho} &= \frac{PD}{2t} \quad \text{or} \quad F_{Ho} = \frac{PD}{2} \qquad (70) \\ \sigma_L &= \frac{PD}{4t} \quad \text{or} \quad F_L = \frac{PD}{4} \qquad (71) \end{aligned}\right\} \text{for unit width}$$

***Oval id Netting Structur*.** This type of structure is simply one that is handled analytically after the appropriate profile for the particular netting system has been derived. The profile is initially determined by an analog device in which a netting of fine threads is constructed. It retains the end-closure fittings. The terminal points of the threads are attached in uniform spacing to a ring representing the circle at which the ovaloid profile becomes tangent to the cylinder. This netting of threads is loaded by utilizing a thin diaphragm like a rubber balloon. For all practical purposes, the entire internal pressure is resisted by thread tension. This tension must of necessity be uniform along the length of each thread. Otherwise, the available friction forces cannot contribute materially to tension gradients along the strands.

The ovaloid profile is presently being studied by analytical means, which have thus far confirmed the philosophy employed in the original analog device. The principal difference in these two approaches relates to the path of the filament along the surface. In the analog study, an arbitrary approach is used. In the initial analytical study, a geodesic path is assumed. The geodesic path is the shortest distance between two points along any surface.

Using either method, it is possible to derive a profile which yields excellent performance. Both methods have shown that there is a fairly precise relationship between the helix angle and the dome shape. The helix angle for the ovaloid windings at the equatorial plane, or the junction between the cylinder and the ovaloid, and the polar-opening diameter are similar.

Unequal Polar Openings (15). When this type of structure is to be built, severe problems develop, especially in units having large diameter-to-length ratios. The polar limits of the ovaloid windings are approximately $0.2R$ at one end and $0.7R$ at the opposite end.

In order to wind a stable pattern over the two ends, it is necessary for the filament to enter one end-winding system at a high helix angle and the other at a low helix angle. This means that the helix angle must vary along the length of the cylinder. A helix angle of changing pitch is not a geodesic path and will slip as the chamber is wound. This slipping will decrease the precision of the winding and degrade structural performance. Very close manufacturing controls are required with this type of unbalance.

Nonpolar Openings. With this type of structure, a major filament-winding problem develops. It is not feasible to wind complex patterns which would bypass such unsymmetrically placed openings. It be-

comes necessary to wind through these areas, incorporating appropriate reinforcing material which will carry the local loads around the opening to be subsequently cut.

Designs are being developed to improve these structural conditions. They have been most successful when applied to circular openings. The loading on the reinforcing members can be determined since the loading on the systems of filaments to be cut is known.

Polar Fittings. Metal and nonmetal fittings are generally wound into the ovaloid end closure to provide attachment details for nozzles, ignitors, etc. The function of these parts is to present enough area to the terminal windings to enable transmission of the loads derived from pressure on the closure plug to the netting system. It can be assumed that all pressure vessels require some form of outlet and/or inlet connections.

Volumetric Expansion. The volumetric expansion of a vessel can be related to its shape and material. A sphere made with homogeneous material and even wall thickness will expand uniformly. A cylinder of similar construction will grow more than four times as much in the circumferential direction as in the axial direction. In filament-wrapped structures expansion or elongation is basically related to the material moduli. In an isotensoid container, uniform stress on

Figure 7.12 Aluminum polar fitting. (Courtesy of NAA Rocketdyne.)

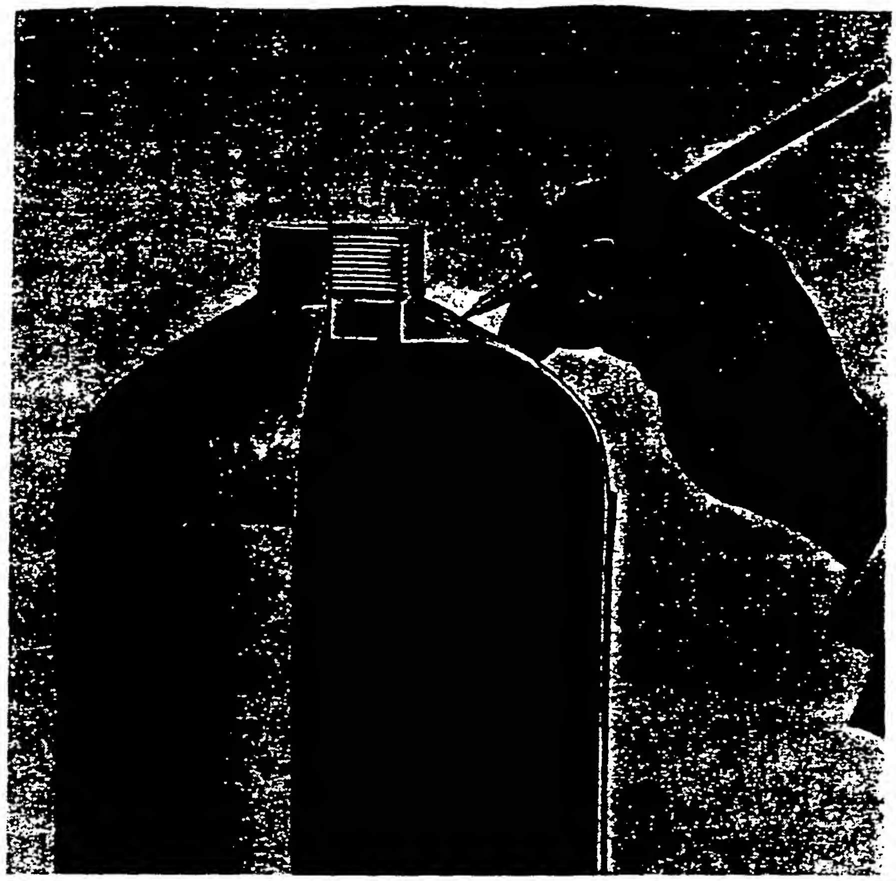


Figure 7.13 Metal end fitting on wound pressure vessel. (Courtesy of Lamtex Industries, Inc.)

fibers occurs, with the result that volumetric expansion is uniform (16).

When structures which are designed and fabricated with nonuniform fiber stress levels are subjected to internal pressure, there will be a tendency to produce a uniform stress distribution. The deformation which occurs increases the rate of volumetric expansion. A higher rate of expansion will occur until uniform stress loads develop.

Designs can be developed so that certain portions of the wall will not change appreciably in any direction under pressurization. With certain design parameters, walls can even contract. Elongation in each direction for filament-wrapped cylindrical vessels is approximately proportional to the amount of material oriented in each direction.

Sandwich Construction. Cylindrical structures are sometimes designed to take both internal and/or external pressures. Previous discussions

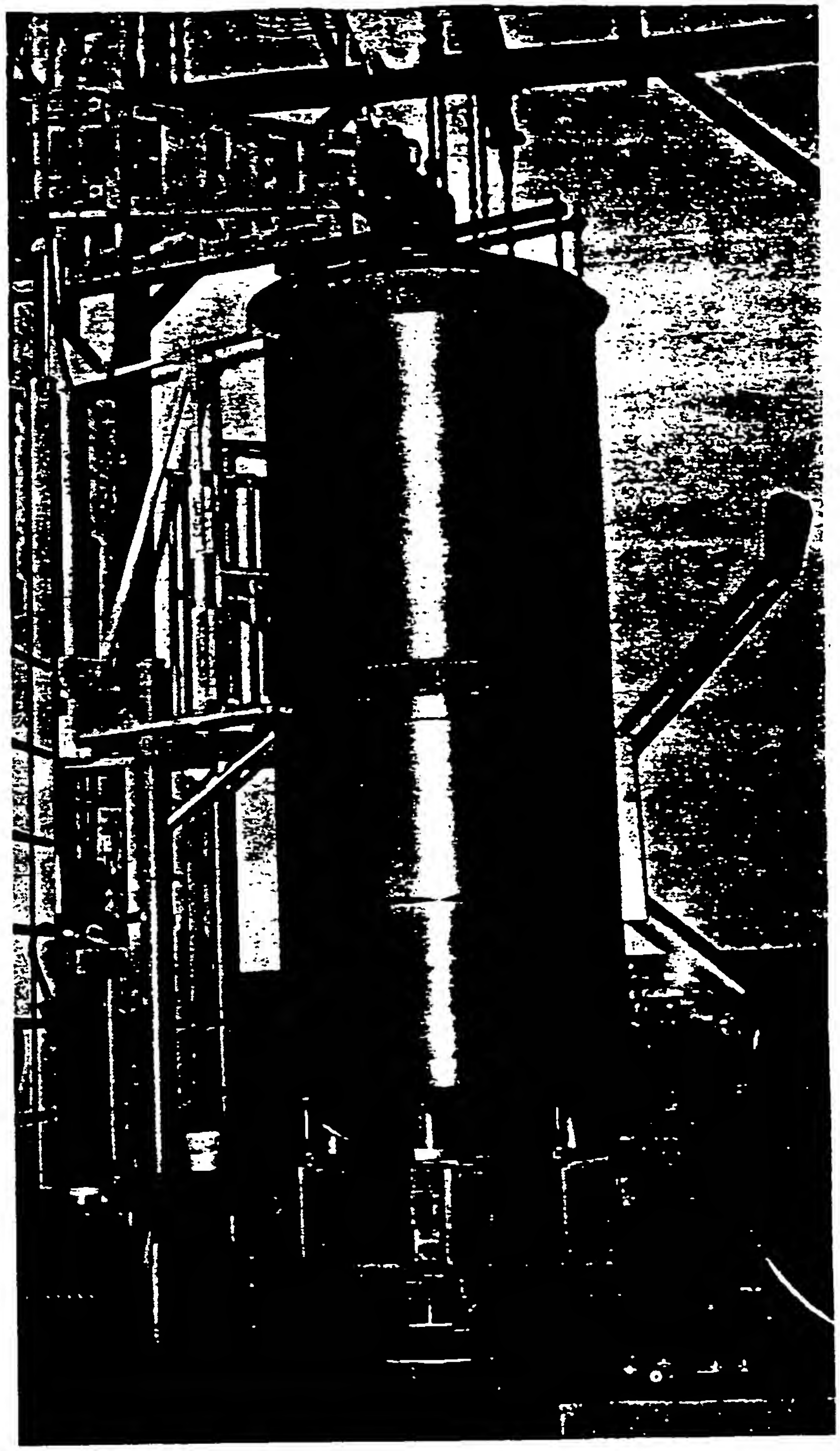


Figure 7.14 Glass epoxy winding around steel rocket motor case. (Courtesy of Brunswick Corp.)

have been specifically related to pressure requirements. In case of weight optimization, however, the difference in the stress levels should be answered. When there are also stiffness requirements, it becomes necessary to increase the wall thickness of the vessel (17).

The stiffness of a structure is a function of the modulus of elasticity and moment of inertia. Since the modulus of elasticity can only remain constant for a given material, a unique solution to the problem is to develop a sandwich construction. A sandwich construction involves the use of two outer reinforced plastic skins with a low-density core material. Since the core material utilized in most cases is of lightweight, open-cell construction, only a minimum shear load can be transferred through the core between faces. This condition complicates methods of analysis. The theories applicable to integral structural analysis can no longer be utilized accurately.

A preliminary design approach can be utilized, which introduces some error. It is adequate for a rough analysis where no exact solution is available. It is assumed that buckling is directly related to the stiffness of the wall. It is also assumed that the sandwich core is capable of transferring shear as well as compression from the external face to the internal face. This approach utilizes a critical buckling equation for a solid homogeneous shell (18).

Filament Winding around Homogeneous Metal Chambers. The optimum structure is a unit wound completely with filament. In developing the optimum unit, different problems can exist with the different winding machines. When fabricating large segmented rocket motor bodies, problems develop such as nonuniform filament tension in heavy-wall construction and attachment of segmented joints. An interim approach being considered, until the filament-wound techniques or machines are perfected, is to use unidirectional hoop-wound filaments around homogeneous metal cylinders. The feasibility of increasing the strength-density ratios of motor cases by this concept has been successfully demonstrated by Aerojet-General Corp. (19).

Steel and titanium cases have been reinforced to increase the strength-density ratio by winding unidirectional hoop filaments over the cylindrical sections of a basic homogeneous case. In general, the case is designed to accommodate only the membrane, bending, and buckling stresses while the reinforcement supports half the hoop stresses. The reinforcement can be applied with the same winding techniques and facilities used in the fabrication of chambers wound completely with filament. To develop rigid and reliable composite

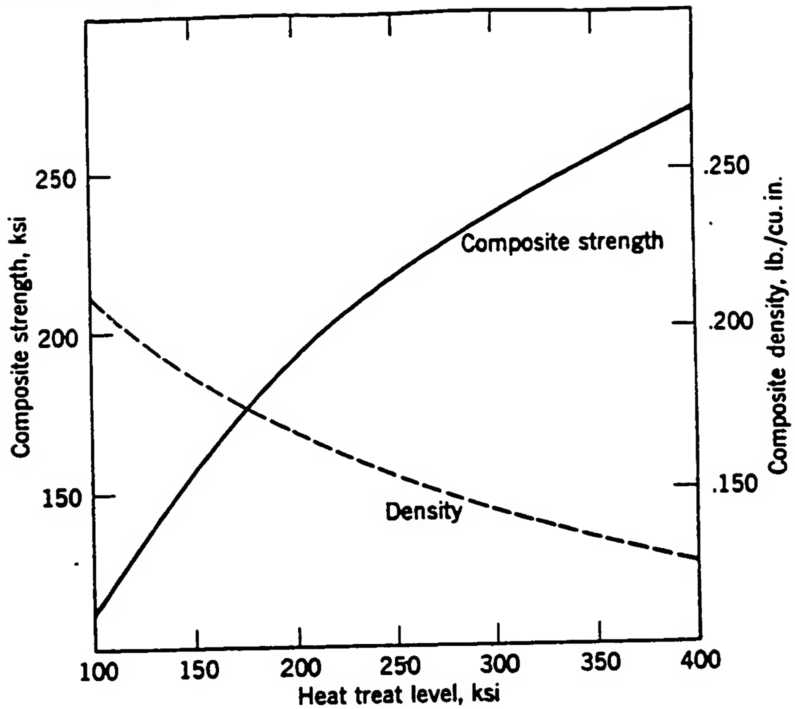


Figure 7.15 Composite glass-resin and steel strengths and density versus heat treat level of glass-resin reinforced steel cylinders with HTS glass—30% resin by volume (19). (Courtesy of Aerojet-General Corp.)

structures, the homogeneous metal material must operate past its yield point. It is important that this design aspect be considered in order to take full advantage of the filament-wound reinforcement strength.

The resulting mechanical properties of the cylindrical section of a reinforced unit are dependent on the strength level of the homogeneous material. In Figure 7.15 the effect of steels heat-treated to biaxial yield strengths of 100,000 to 400,000 psi is compared to the composite strengths and densities. Note that the rate of increase (slope of the curves) in the strengths decreases as the heat-treat level increases. In Table 7.4 mechanical properties of reinforced homogeneous rocket motors are summarized.

A typical composite test was conducted on a shear-spun Ladish D6aC steel forged and machined preforms as shown in the 18.25-inch cylinder assembly drawing of Figure 7.16. Two circumferential welds joined three sections. The glass-filament reinforcement, which used seven layers of 0.007-inch-thick E-glass rovings with Dow 135 resin, permitted burst to occur simultaneously in the hoop and longitudinal directions. Figure 7.17 shows the theoretical stress-strain curve for

Table 7.4 Mechanical Properties of Reinforced Homogeneous Chambers (19)

Homogeneous Material	Homogeneous Biaxial Yield, psi	Homogeneous Density, pounds/cubic inch	Composite * Ult. Str., psi	Composite Density, Pounds/Cubic Inch	Clt. Str./ Density,* 10^6 inches	Equivalent * St el Alloy Strength, psi
Steel Alloys						
4130	150,000	0.283	170,000	0.194	.878	250,000
	175,000	0.283	185,000	0.187	1.00	283,000
M255	200,000	0.283	197,800	0.180	1.1	312,500
	225,000	0.283	209,000	0.174	1.21	345,000
20 to 25% Nickel	250,000	0.285	219,000	0.167	1.31	374,000
	275,000	0.285	228,000	0.163	1.41	400,000
	300,000	0.285	236,000	0.159	1.48	422,000
Titanium Alloys						
6Al-4V	150,000	0.063	170,000	0.126	1.35	385,000
	175,000	0.163	185,000	0.123	1.51	429,000
6Al-6V-2Sn	200,000	0.163	197,800	0.121	1.63	465,000
	225,000	0.163	209,000	0.117	1.78	509,000

* Assuming homogeneous ultimate strength equal to yield strength and use of type HTS glass filaments.

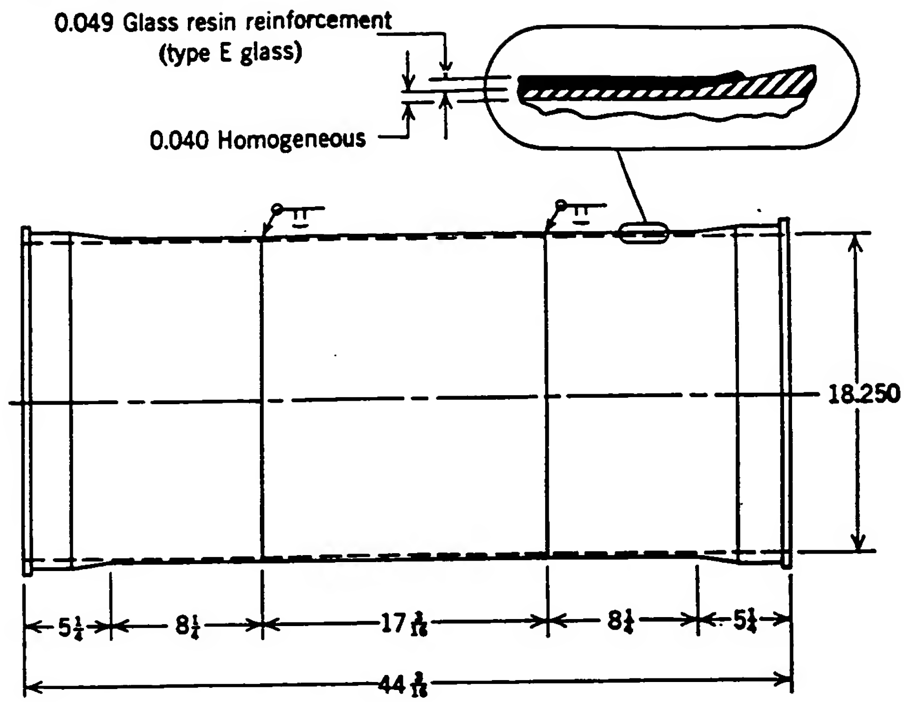


Figure 7.16 Glass-resin reinforced homogeneous D6aC steel cylinder assembly (19).

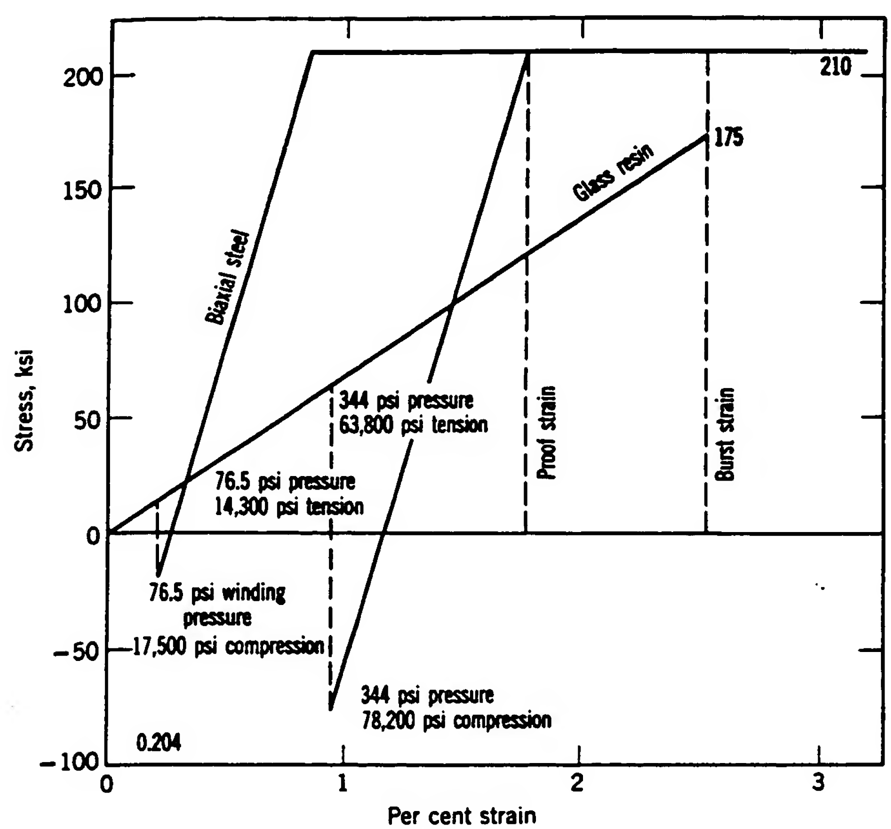
this design configuration. The theoretical pressure-strain curve is shown in Figure 7.18.

Another test vehicle was the approximate 8-inch-diameter Sparrow missile rocket motor body configuration as shown in Figure 7.19, using a 25 per cent nickel-alloy steel homogeneous material. Reinforcement of five layers of 0.007-inch-thick HTS glass rovings with Dow 332 resin was designed to permit burst in the hoop direction. In Figures 7.20 and 7.21 the theoretical stress-strain curve and pressure-strain curve for this unit are shown.

These curves show that when the proof pressure is removed, the reinforcement will relax along a line offset but essentially parallel to the original modulus line. A new equilibrium condition is reached, wherein the compressive load on the steel is in equilibrium with the tensile load on the glass reinforcement. The pressure curves show that, up to the steel yield point, both materials contribute constantly increasing strength in resisting the internal pressure. Beyond the steel yield point, the steel level is constant, while the reinforcement load increases in a direct relationship to its modulus. This produces a composite pressure-strain curve that reaches the yield strain of the steel at a pressure equal to the load capability of the steel plus the

reinforcement capability at this strain value. Beyond this point, the composite curve rises to proof or burst pressure along a path parallel to the pressure-strain characteristic of the glass (E or HTS type).

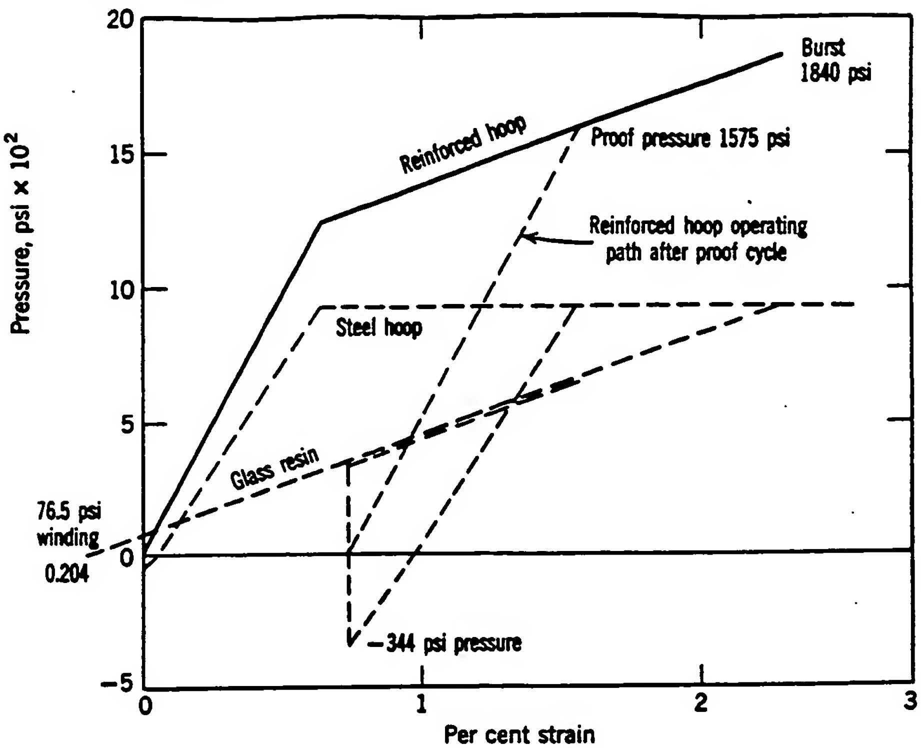
Hydrostatic tests were conducted on different composite chambers. Figure 7.22 shows the typical failure of an 18.25-inch cylinder after burst. This cylinder was basically constructed in a similar manner to the 18.25-inch just reviewed, except that HTS-glass replaced the E-glass. It was subjected to 1,550 psi proof test and pressurized to burst. Failure occurred at 1,774 psi in the longitudinal mode with a complete circumferential girth failure. Design burst pressure was 1,840 psi. With the E-glass cylinder, two proof cycles were applied



18.250″ inside diameter
1,840 psi burst pressure
0.040″ D6aC steel
0.049″ "E"-Glass resin

Strength/density: 1.12×10^6
Equivalent: 318,000 psi UTS
Glass strain at burst: 2.5%
Composite strain at burst: 2.296%

Figure 7.17 Theoretical stress-strain relationship glass-resin reinforced steel cylinder (19).



18.250″ inside diameter
1,840 psi burst pressure
0.040″ D6aC steel
0.049″ "E"-Glass resin

Strength/density: 1.12 × 10⁶
Equivalent: 318,000 psi UTS
Strain at burst: 2.296%

Figure 7.18 Theoretical pressure-strain relationship glass-resin reinforced steel cylinder (19).

(first to 1,425 psi and second to 1,575 psi) before it was subjected to burst. Failure occurred at 1,750 psi. Its design burst pressure was 1,840 psi.

In Figure 7.23 a typical pressure-strain curve is shown, based on recorded data obtained during an actual hydrostatic test. A glass-resin curve based on moduli that have been adjusted for actual resin content, winding tension, and reinforcement thickness has been superimposed. The slope of the superimposed glass-resin curve is essentially identical to that of the steel-glass composite curve beyond the yield point. This characteristic indicates that the glass is carrying all of the increasing hoop load. The steel hoop curve was obtained as the difference between the curves for the reinforced material and the glass resin.

Table 7.5 presents a comparative summary, based on results obtained

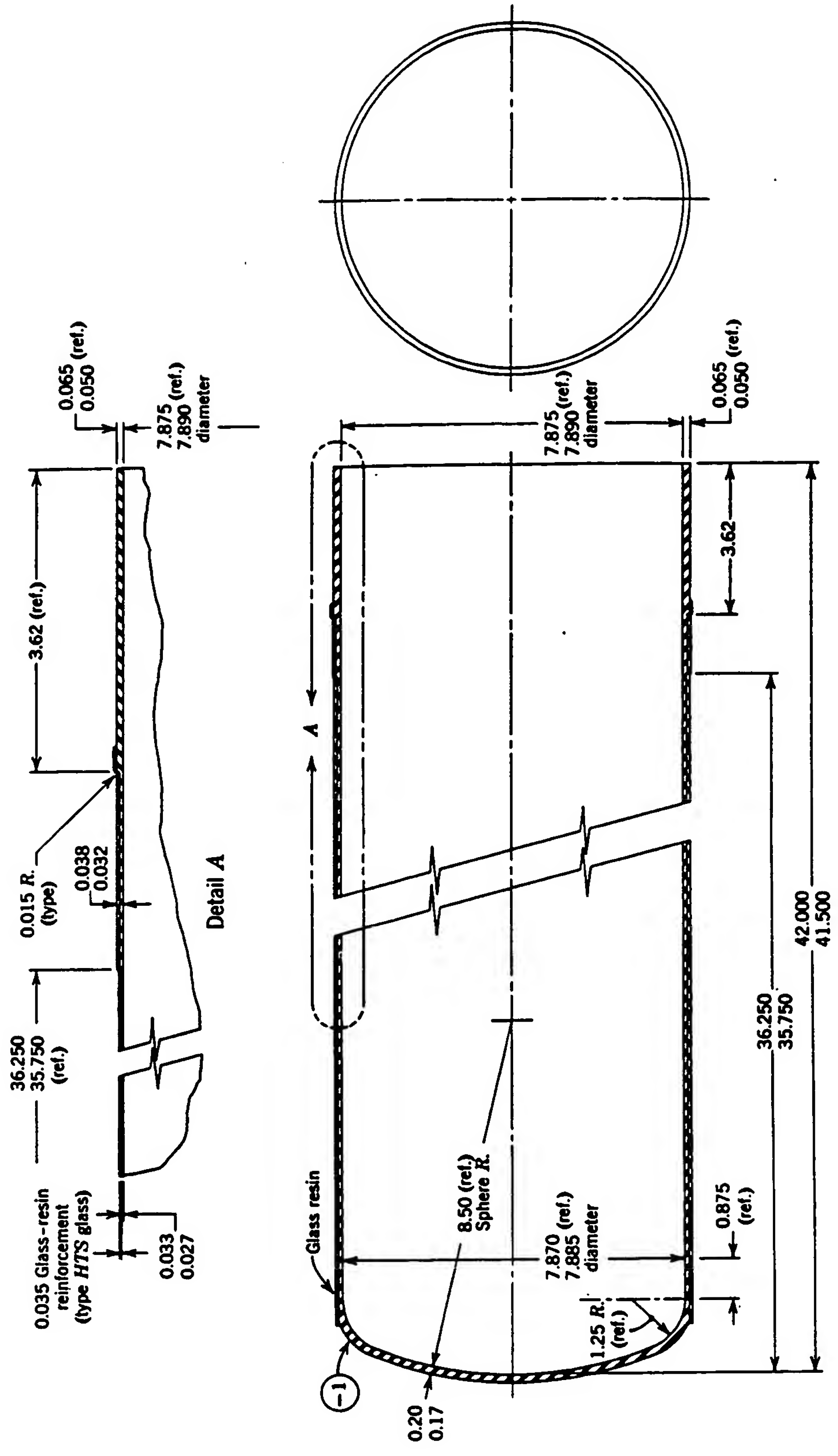
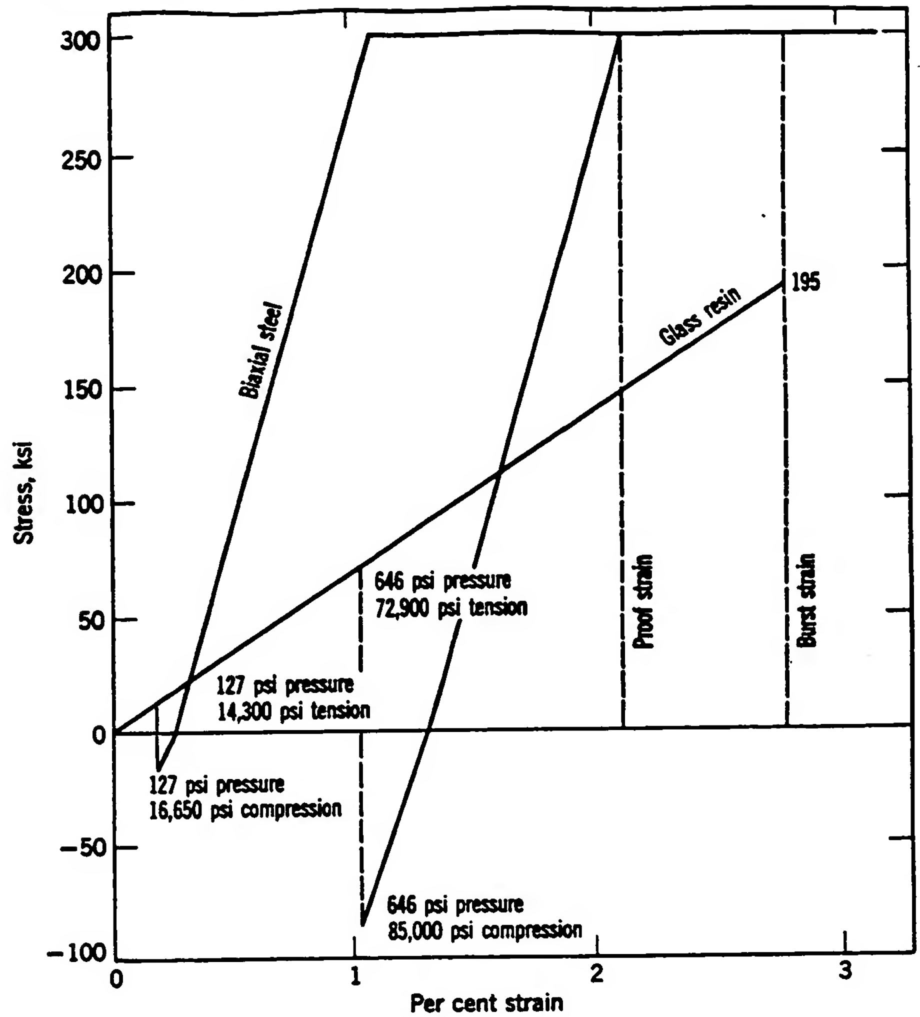


Figure 7.19 Glass-filament reinforced homogeneous nickel alloy chamber assembly (19).



7.890″ inside diameter
4,005 psi burst pressure
0.030″ 25% high nickel-alloy steel
0.035″ HTS glass resin

Strength/density: 1.41×10^6
Equivalent: 402,000 psi UTS
Glass strain at burst: 2.785%

Figure 7.20 Theoretical stress-strain relationship glass-resin reinforced Sparrow (19).

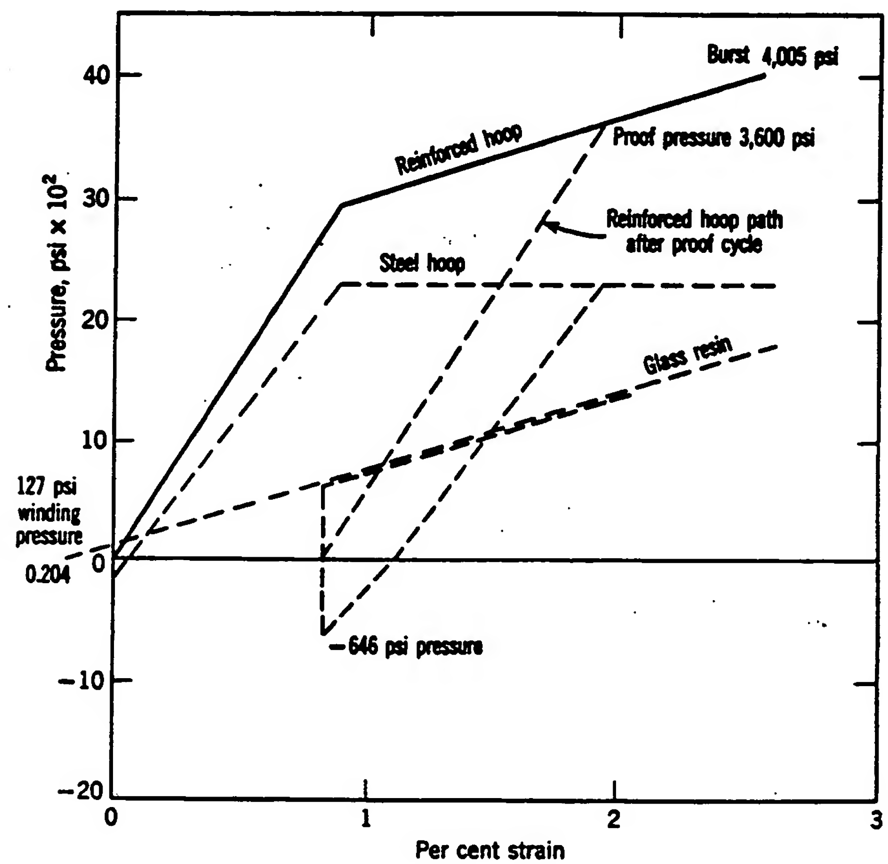
during actual tests and design values. The investigators' analysis of the data presented indicates (19).

(*a*) Hoop steel biaxial yield strengths averaged about 13 per cent higher than the uniaxial yield strengths. The factor originally assumed in designing the units was 10 per cent.

(*b*) Essentially constant steel hoop strength was realized from yield to burst. This verifies one of the original design assumptions.

(*c*) Longitudinal steel biaxial yield strengths averaged about 88 per cent of the uniaxial strengths rather than the 95 per cent originally assumed. As a result, the 0.2 per cent offset yield points were exceeded slightly at 90 per cent proof pressures.

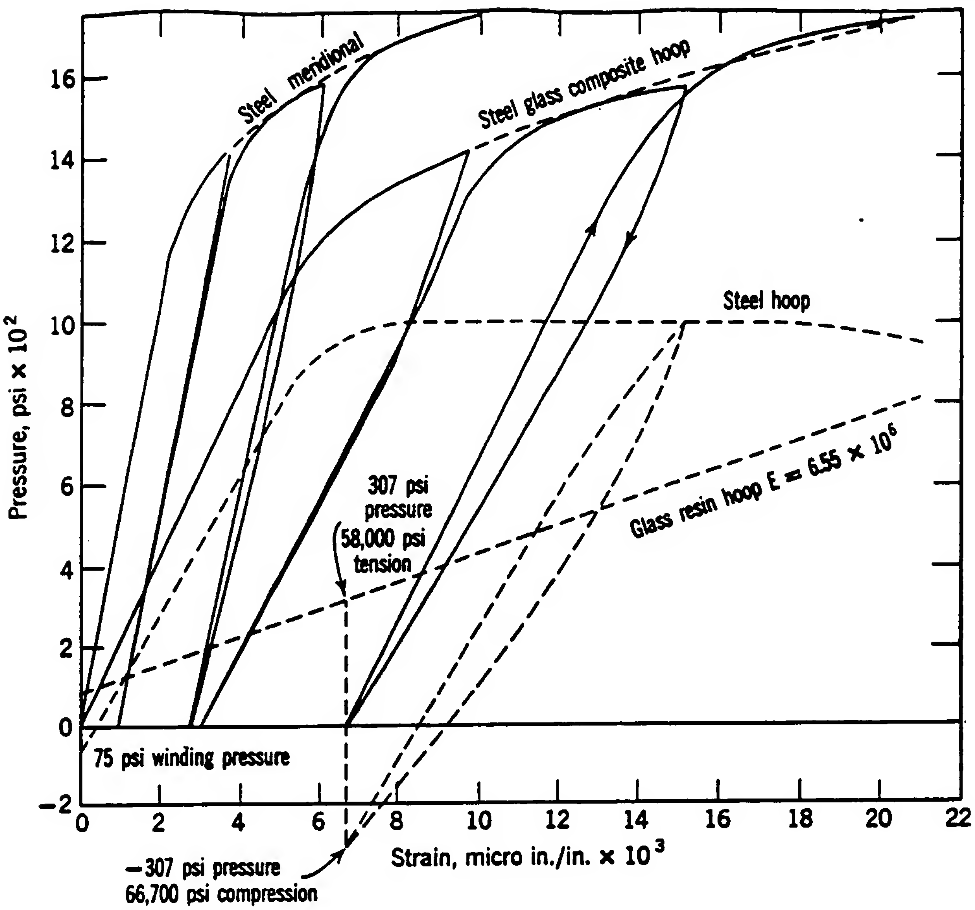
(*d*) Glass-filament stresses of 230 ksi for E-glass and 238 and 256 ksi for HTS-glass were realized in those units that did not fail prematurely because of imperfections in the structure. Higher stresses could have been realized on the HTS units if hoop burst had been obtained rather than longitudinal burst. The E-glass strength represents an efficiency of 92.5 per cent, based on the minimum 250 ksi guaranteed



7.890" inside diameter	Strength/density: 1.41×10^6
4,005 psi burst pressure	Equivalent: 402,000 psi UTS
0.030 25% high nickel-alloy steel	Strain at burst: 2.581%
0.035 HTS glass resin	Total glass strain at burst: 2.785%

Figure 7.21 Theoretical pressure-strain relationship glass-resin reinforced Sparrow (19).

Figure 7.22 Glass-filament reinforced homogeneous D6aC steel cylinder after hydrostatic burst test (19). (Courtesy of Aerojet-General Corp.)



18.250" inside diameter
D6aC steel-type "E" glass
Data from steel gage No. 4
Thickness of steel at gage: 0.042"
Thickness of glass resin: 0.048"

Strength/density: 1.07×10^6
Equivalent: 303,000 psi UTS
Composite strain at burst: 2.1%
Glass strain at burst: 2.3%

Figure 7.23 Actual pressure-strain relationship of glass-resin reinforced steel cylinder (19).

material UTS, while the HTS-glass strength represents efficiencies of 85.5 and 92 per cent when based on the minimum 280 ksi guaranteed material UTS.

(*e*) The hoop-to-longitudinal stress ratio at hoop yield averaged 1.48, while the hoop-to-longitudinal stress ratio at longitudinal yield averaged 1.33. The 1.33 figure is higher than the 1.16 figure expected and directly correlates with the low longitudinal yield strengths mentioned in *c*.

Fastenings. There are different types of mechanical fasteners suitable for joining conventional reinforced plastics. Insofar as reinforced

Table 7.5 Mechanical-Property Test Data, Glass-Resin-Reinforced Homogeneous Chamber Program (19)

Test Number	18.250-Inch-Diameter D6aC Steel, E Glass		18.250-Inch-Diameter D6aC Steel, HTS Glass		7.890-Inch-Diameter Sparrow Units 4,130 Steel, HTS Glass					7.890-Inch-Diameter Sparrow Units 25% Nickel Alloy, HTS Glass
	Design	Actual 412K	Design	Actual 607K	Design	Actual 608K	Actual 609K	Actual 610K	Actual 611K	Design
Homogeneous Material										
Thickness, inches	.040	.040	.040	.042	.026	.028		.028	.027	.030
Uniaxial yield, ksi	190	194	190	177	160	162		163	164	275
Uniaxial ultimate, ksi	230	216	230	200	180	178		184	184	310
Biaxial hoop yield, ksi	210	215	210	200	175	185		188	186	300
Biaxial hoop ultimate, ksi	210	207	210	203[2]	175	170[5]		192	188	300
Biaxial long yield, ksi	180	166	180	158	152	147		145	141	256
Biaxial long ultimate, ksi	230	190[1]	230	193	180	175		160[6]	142[7]	310
Hoop/long stress, hoop yield	1.52	1.47	1.58	1.44	1.55	1.50		1.50	1.49	1.57
Hoop/long stress, long yield	1.17	1.32	1.17	1.33	1.16	1.32		1.32	1.31	1.16
Hoop/long stress, burst	1.00	1.09	1.00	1.07	1.00	.92		1.27[6]	1.31[7]	1.00
Glass-Resin										
Reinforcement thickness, inches	.049	.048	.042	.046	.028	.028		.029	.030	.035
Resin by volume, per cent	30	34.5	30	35.2	30	28.3		32.3	34	30
Modulus of elasticity, 10^6 psi	7.00	6.55	7.00	6.48	7.00	7.17		6.77	6.60	7.00
Reinforcement stress, at burst, ksi	175	151	195	154[3]	172	184		103[6]	97.7[7]	195
Filament stress at burst, ksi	250	230	280	238[3]	245	256		153[6]	148[7]	280
Per cent minimum filament UTS	100	92.5	100	85.5[3]	87.8	92		55[6]	53[7]	100
Total Composite										
Burst area	Simultaneous	Hoop	Simultaneous	Long	Long[4]	Long		Hoop	Rivets	Hoop
Burst pressure, psi	1,840	1,750	1,840	1,774	2,370	2,500		2,120	2,174	4,006
Effective wall strength, psi	190,700	181,900	202,500	185,000[3]	173,500	176,000		140,000[6]	161,000[7]	243,500
Density, pounds/cubic inch	.1704	.1702	.178	.174	.177	.1808		.177	.178	.173
Effective Str./Density, 10^6 inches	1.12	1.07	1.135	1.07[3]	.98	.975		.790[6]	.85[7]	1.41
Effective Equiv. Steel Strength, ksi	318	303	323	302[3]	278	277		226[6]	241[7]	402

[1] At time of hoop burst.
[2] At time of longitudinal burst.
[3] Full capability not developed because of longitudinal burst. Strength level of homogeneous material below spec.
[4] Unit design for longitudinal burst, so full hoop capability would not be developed.
[5] At time of longitudinal burst.
[6] Premature hoop burst in an area where an apparent defect was noted before test. This resulted in low values.
[7] Premature burst when unit failed in area of closure rivets.

plastic filament-wound structures are concerned, it is best to design the system so that no joining or a minimum of joining requirements exist after the part is fabricated.

Conventional fastening processes applicable to reinforced plastics are generally identified as adhesive or mechanical types (20). To date, with the limited amount of development and/or production requiring fasteners on filament-wound structures, the general approach involves the use of adhesives. The trend is not to apply mechanical fasteners, since stressed fibers would be destroyed.

When fastening reinforced plastics (not filament-wound), mechanical joint efficiencies as low as 30 per cent are not uncommon. Joint efficiencies from 50 to 80 per cent can readily be achieved with adhesives. In filament structures, if mechanical joints are required the original design parameters will have to take into consideration the effect of holes or inserts. Since filament-wound structures tend to expand or contract when subjected to internal or external loads, definite problems develop in producing useful adhesive joints.

Mechanical fastenings are easily included in filament-wound structures but generally at the sacrifice of developing the most efficient

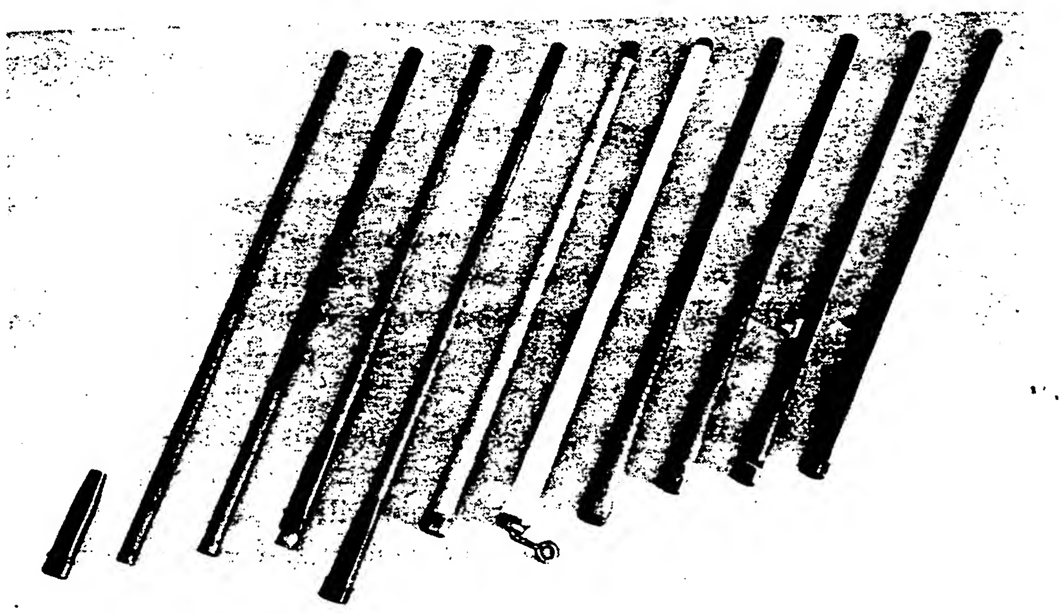


Figure 7.24 Stages in manufacture of glass-fiber-wound shotgun barrels; from left to right, model liner part, four steps in metal parts assembly, filament-wound barrel, convolute wrapped, resin impregnated, shaped-sanded, lug and sight bonded in place, and finished barrel.

structure. Thicker filament structures are required to support concentrated loads. Of course, if the filament structure requires inclusion of mechanical fasteners, then fundamentally no sacrifice occurs.

BASIC RELATIONSHIPS GOVERNING IDEAL STRUCTURES

One of the principal items made from filament-wound plastics is the internal pressure vessel. This is usually cylindrical in shape and, both for access and for manufacturing, comes equipped with ports on the axis of the vessel at each end. The ends themselves, which join to this cylindrical part, may be designed with a curve. The filaments may be laid down at any angle to the axis of the vessel in the form of a spiral. In addition to this spiral winding, manufacturing simplicity sometimes permits windings circumferentially around the barrel of the cylindrical section and also lengthwise from end to end. Certain combinations of thicknesses of these spiral, hoop, and lengthwise windings are possible, and the shape of the end closures to give the most satisfactory results is predictable from theory. The problem is to decide what the most satisfactory results might be and then to design to meet these criteria. Dr. John O. Outwater, professor of Mechanical Engineering at the University of Vermont, has developed the following criteria to provide a practical approach for the designer (21).

Filament-wound materials are used to give the strongest possible vessel for the weight of glass involved. Knowing this, we can formulate some logical assumptions about design.

1. All the filaments in the vessel should be under the same tensile stress. Underloaded filaments merely add weight.
2. There will be no bending moment in the wall of the vessel during load. If there were bending, the outermost fibers would be under greater load than the inner ones and the primary condition of equal load would be violated.
3. All the strength is contributed by the longitudinal tensile strength of the filaments. Because the elastic modulus of the resin is much less than that of the glass, it will contribute very much less to the vessel strength. This contribution should be ignored, as well as any shear contribution of the resin, particularly after the vessel has been loaded and crazing appears. The resin cannot carry any load across these cracks.
4. The vessel is symmetrical and consists of a cylindrical section with end closures containing a center hole, which is subsequently capped.

5. Compared with the diameter of the vessel the thickness of the case is not great. Thus, we can assume that the diameter of the cylinder to inner or outer fibers is the same.

6. All filaments are free to adjust themselves during manufacture so that no unequal tensions will be introduced and the filaments will be loaded equally along their entire lengths. This is valid with wet winding in particular, as there will be a tendency to slip if there is any difference in tension along their lengths.

7. There is no shear transfer from one winding to another. This analysis, in fact, assumes that we are analyzing what might be visualized as a "string wound, flexible bag," containing an internal pressure.

8. The windings are applied either as longitudinal, hoop, or helical windings, in line with practical techniques. It should be noted that the helical windings will result in crossed filaments with the same number of filaments in each crossed spiral direction.

9. The windings are applied under slight tension so circumferential windings become impractical on the end closures. Because of the slope they would tend to come unstuck and would slide toward the axis.

10. The longitudinal windings are continuous throughout the length of the vessel.

11. The helical windings are applied continuously throughout the length of the vessel.

12. The loading within the vessel is hydrostatic.

All these assumptions are in accord with practical manufacturing techniques and are necessary to analyze properly the geometry and stresses within the vessel walls.

In this study we shall analyze the vessel in two parts, the cylindrical section and the end closures.

Consider that the filament-wound pressure vessel (as shown in Figure 7.25) has a diameter D and an internal hydrostatic pressure p. Its overall wall thickness t is composed of longitudinal windings having a thickness t_l, hoop windings of thickness t_h, and helical windings of thickness t_θ, which are applied at an angle θ to the longitudinal axis of the cylindrical vessel. Also, according to our first basic assumption, the filament-wound cylinder is ideal, that is, each filament in any of the windings is to be stressed by the same amount S.

For any cylindrical pressure vessel with end plates, the loading or stress in the wall of the vessel can be resolved into two components, the longitudinal component S_l, acting parallel to the axis of the cylinder, and the hoop stress S_h. Since the vessel is symmetrical, the

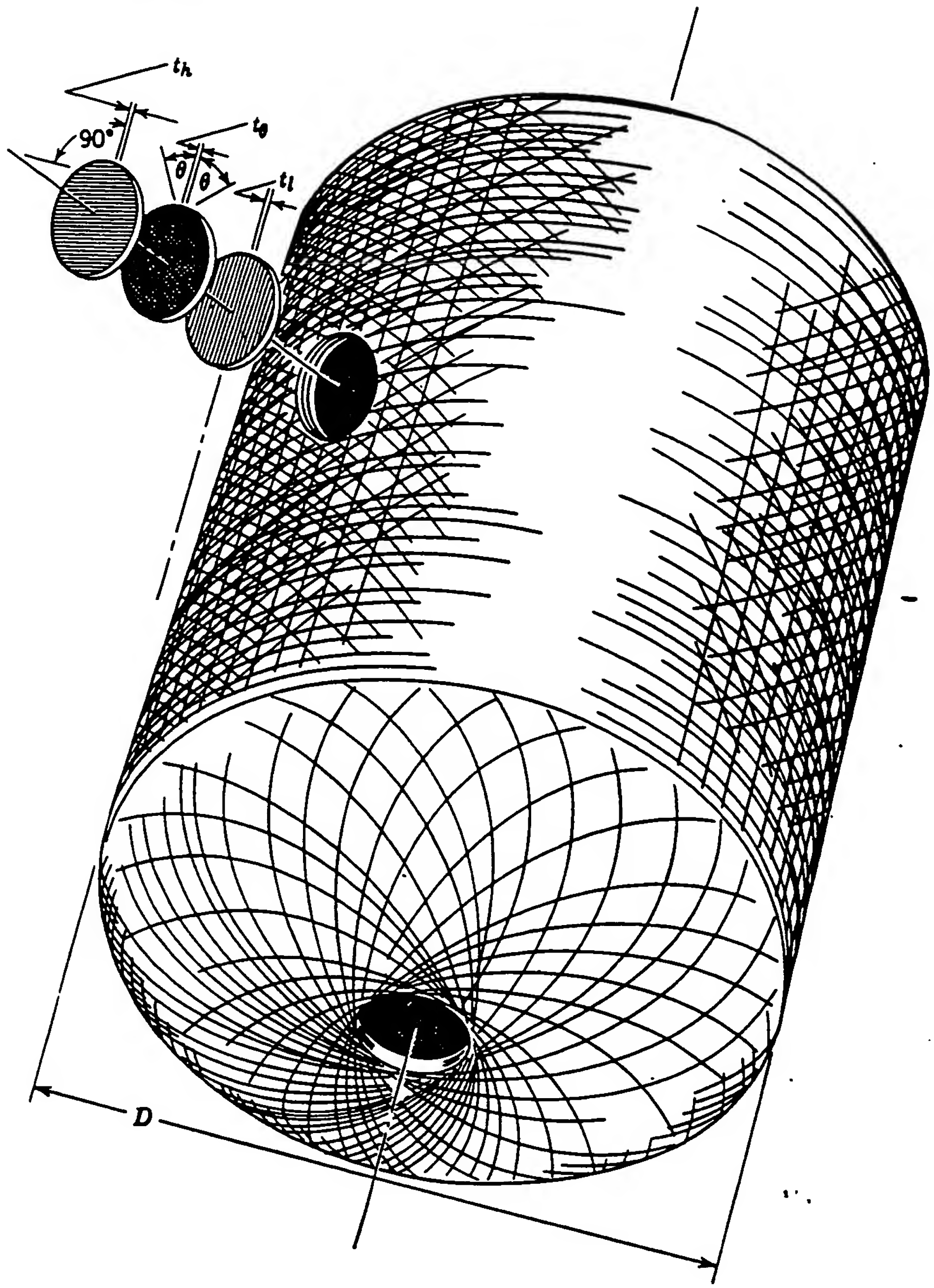


Figure 7.25 Diagram of filament-wound pressure vessel having longitudinal, meridional, and helical windings (21).

principal axes will be in these directions, and hence there will be zero shear stress in these directions.

It has been shown that the hoop or meridional stress S_h in such a pressure vessel will depend on the internal pressure, vessel diameter, and vessel wall thickness according to the following relationship:

$$S_h = \frac{pD}{2t} \tag{72}$$

It has also been shown that the hoop stress in the loaded vessel is always twice that of the longitudinal stress S_l or

$$S_h = 2S_l \tag{73}$$

In addition since the shell of the vessel under consideration is made of hoop, longitudinal, and helical windings, S_h will be the sum of the components of stress in the hoop windings and the hoop stress component produced by the helical winding; the longitudinal winding and longitudinal component of the helical windings act at right angles and do not contribute to the hoop stress. By a force balance per unit length of wall cross section parallel to the cylinder's axis,

$$S_h = \frac{S_h' t_h}{t} + \frac{S_{h\theta} t_\theta}{t} \tag{74}$$

where S_h' is the stress in the hoop winding layer (and which is by definition equal to S), $S_{h\theta}$ is the hoop component of the stress in the wall contributed by helical winding, and t, t_h, and t_θ are thicknesses as defined earlier.

Similarly, the longitudinal wall stress

$$S_l = \frac{S_l' t_l}{t} + \frac{S_{l\theta} t_\theta}{t} \tag{75}$$

and by Equation 73

$$\frac{S_h}{2} = \frac{S_l' t_l}{t} + \frac{S_{l\theta} t_\theta}{t} \tag{76}$$

where S_l' is the stress in the longitudinal winding layer (by definition equal to S), $S_{l\theta}$ is the longitudinal component of the stress in the wall, contributed by the helical winding, and other terms have been defined earlier. Note also, by definition

$$S_h' = S_l' = S \tag{77}$$

With reference to Figure 7.26, we can write the following relationship based on the geometry of two of the filaments of the helical windings

$$2SA \sin\theta = S_{h\theta} \frac{2A}{\sin\theta} \tag{78}$$

or

$$S_{h\theta} = S \sin^2\theta \tag{79}$$

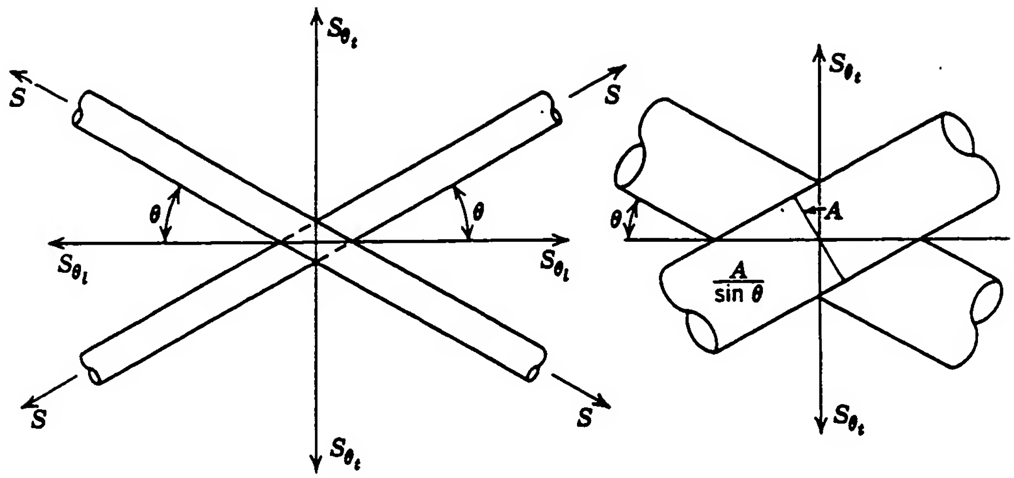


Figure 7.26 Diagram showing helical winding stresses (21).

and similarly the longitudinal component of the helical winding stress

$$S_{l\theta} = S\cos^2\theta \tag{80}$$

If Equations 79 and 80 are added, it becomes obvious that

$$S_{h\theta} + S_{l\theta} = S(\sin^2\theta + \cos^2\theta) = S \tag{81}$$

at all times if the stresses in all winding filaments are equal, that is, if the vessel is ideal or properly designed.

In addition to the preceding relationships for the stresses within the ideal cylinder, one may obtain another relationship between the filament stress S and the total hoop stress S_h and the total longitudinal stress S_l in the vessel wall by using Equations 74, 75, 77, 79, and 80 and remembering that

$$t = t_h + t_l + t_\theta \tag{82}$$

By substitution, Equations 74 and 75 become

$$S_h = \frac{St_h}{t} + \frac{S\sin^2\theta t_\theta}{t} \tag{83}$$

and

$$S_l = \frac{St_l}{t} + \frac{S\cos^2\theta t_\theta}{t} \tag{84}$$

By adding Equations 83 and 84, it may be shown that

$$S = S_h + S_l \tag{85}$$

With this relationship it is then possible to develop the formula for the overall wall thickness of the ideal filament-wound vessel.

Remembering that

$$S_h = 2S_l = \frac{pD}{2t} \tag{86}$$

by rearrangement we find

$$t = \frac{pD}{4S_l} \tag{87}$$

and by Equations 85 and 86 it may be shown that

$$S_l = S/3 \tag{88}$$

so that Equation 87 becomes

$$t = \frac{3pD}{4S} \tag{89}$$

Since the allowable fiber or filament stress S is usually known, and since the internal working pressure p and the diameter of the vessel are given, it becomes possible to calculate the overall wall thickness of the vessel which will produce the ideal loading or equivalent stress in each filament. Note that the overall wall thickness does not depend on the thicknesses of the individual winding layers or on the helical winding angle; it is dependent only on the diameter of the vessel, the internal pressure, and the allowable fiber stress.

However, although the overall thickness is not dependent on the helical winding angle or the relative thicknesses of the hoop, longitudinal, and helical windings, the thickness of each of the types of windings and the winding angle are interrelated because of the basic geometrical characteristics of the cylindrical pressure vessel and the requirement that fiber stress be equivalent in each winding layer. Fixing the helical winding angle at some value other than 90° or, in other words, introducing any thickness of helical winding will require that the thickness of the hoop and longitudinal windings be reduced to maintain the ideal pressure cylinder relationships. Formulae relating the thickness of the various layers are developed as follows.

Remembering that the hoop stress S_h is twice the longitudinal stress and using Equations 83 and 84, we obtain

$$St_h + S\sin^2\theta t_\theta = 2St_l + 2S\cos^2\theta t_\theta \tag{90}$$

or

$$t_\theta = \frac{2t_l - t_h}{\sin^2\theta - 2\cos^2\theta} \tag{91}$$

or

$$t_\theta = \frac{2t_l - t_h}{1 - 3\cos^2\theta} \tag{92}$$

since $\sin^2\theta = 1 - \cos^2\theta$. Also by solving Equations 82 and 92 simultaneously (subtracting Equation 92 from Equation 82 to solve for t_l and then using Equation 82 to solve for t_h, the following equations result:

$$t_l = \frac{t}{3} - t_\theta \cos^2\theta \tag{93}$$

and

$$t_h = \frac{2t}{3} - t_\theta \sin^2\theta \tag{94}$$

As a check on the equations, when t_θ is zero, t_l equals $t/3$ and t_h is equal to $2t/3$ or t_h is equal to $2t_l$, which is what one would require in a cylindrical vessel having no helical windings in which the fiber stress in the hoop and longitudinal windings must be equivalent.

To illustrate the use of the equations, consider the design of a pressure vessel required to contain an internal pressure of 100 pounds per square inch absolute, 12 inches in diameter, made of glass fibers which have an ultimate tensile strength of 150,000 pounds per square inch absolute, and assume that a safety factor of 2 is to be used. Assume no longitudinal windings, only hoop and helical windings ($\theta = 30°$).

The first step is to calculate the overall thickness of the vessel. Since a safety factor of 2 is to be used, $S = 75{,}000$ pounds per square inch absolute and by Equation 89

$$t = \frac{3pD}{4S} \tag{95}$$

$$= \frac{(3)(10^2)(12)}{(4)(7.5 \times 10^4)} = \frac{36}{30} \times 10^{-2} \tag{96}$$

and

$$t = 0.012 \text{ inches} \quad \text{or} \quad 12 \text{ mils} \tag{97}$$

Using Equation 94 and recognizing that when there are no longitudinal windings, $t_\theta = t - t_h$, one may calculate the thickness of the hoop windings as shown below.

$$t_h = 2t/3 - (t - t_h)\sin^2\theta \tag{98}$$

$$= \frac{(2)(1.2)(10^{-2})}{3} - (1.2 \times 10^{-2} - t_h)(0.5)^2$$

$$= 0.008 - 0.003 + 0.25t_h$$

$$= \frac{0.005}{0.75}$$

$$= 0.00666 \text{ inches or } 6\tfrac{2}{3} \text{ mils} \tag{99}$$

then $t_\theta = 5\frac{1}{2}$ mils or 0.00533 inches. As a check we may rearrange Equation 94, then,

$$t_\theta = \frac{2t - 3t_h}{3 \sin^2 \theta} \tag{100}$$

$$= \frac{(0.024 - 0.020)}{(3)(0.25)} = \frac{0.004}{0.75}$$

$$t_\theta = 0.00533 \text{ inches} \tag{101}$$

The usefulness of such equations is obvious. They allow the processor to design his filament-wound cylindrical pressure vessels so that maximum utilization of the inherently high tensile strength of the glass or other fiber reinforcement will be realized.

The end closures of a pressure vessel are designed so that the cylindrical part will fair smoothly into them and at the same time give no bending within them. We will design for a central hole, and the purpose is to enable us to compute the curve needed for these ends and the thicknesses of windings that will satisfy the earlier conditions for the cylindrical section. Practical considerations demand that the longitudinal windings in the cylindrical section be continued to the ends over the end sections and that the helical windings do the same.

Consider the construction of a small area of the end closure at a radius r from the axis. Let the radii of curvature of this area be R_l and R_t in the directions shown in Figure 7.27. Let its total thickness be t_e, which is made up of thicknesses t_{le} and $t_{\theta e}$ in the longitudinal and helical directions. We should note here that hoop windings are impractical on the end closures because they tend to slide down during winding. In calculating for end closures without hoop windings, the helix angle at any point will be θ_e in its inclination to the meridian, and the inclination of the tangent plane of the small area to the axis will be A. The component stresses at this area are S_{le} and S_{te} in the longitudinal and tangential directions.

Many mathematical relations can be made for the end closures: first, since the thickness is made up of helical and longitudinal windings,

$$t_e = t_{\theta e} + t_{le} \tag{102}$$

If there is no bending in the end closure surface,

$$\frac{S_{le}}{R_l} + \frac{S_{te}}{R_t} = \frac{p}{t_e} \tag{103}$$

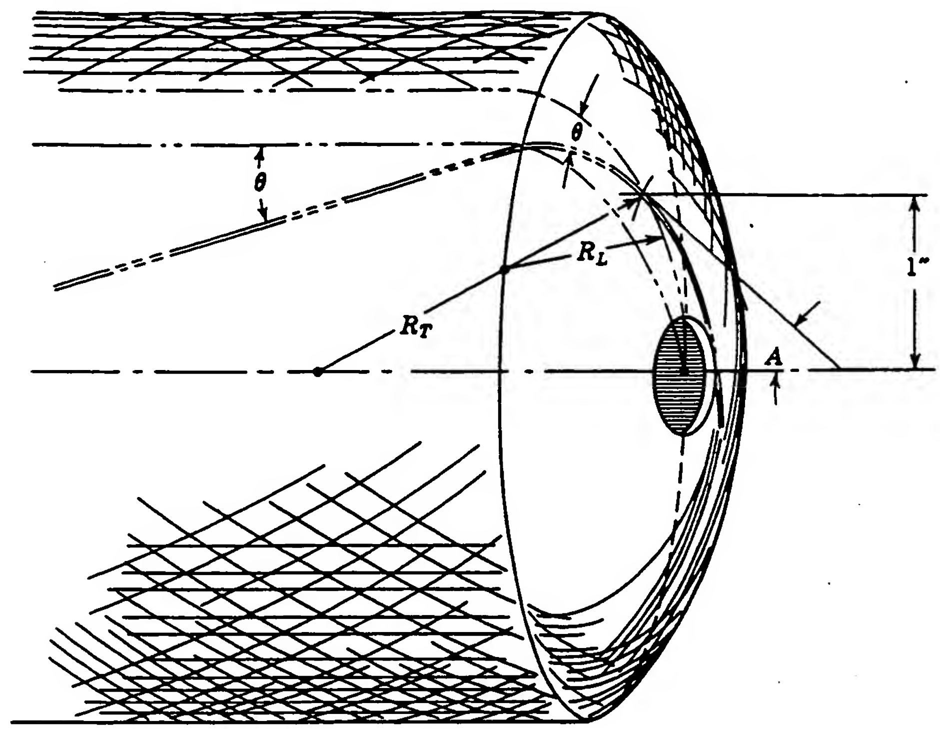


Figure 7.27 Diagram showing typical winding pattern used on end closures (21).

Geometrically,

$$R_t = \frac{r}{\cos A} \tag{104}$$

By considering the equilibrium of the end across a transverse section,

$$p\pi r^2 = S_{le} t_e (2\pi r \cos A) \tag{105}$$

or by rearrangement,

$$\frac{pr}{2t_e} = S_{le} \cos A \tag{106}$$

Since the longitudinal fibers will be constant in number, and hence in area, along their length, we can relate their thickness at any point

$$t_{le} = t_l \left(\frac{D}{2r}\right) \tag{107}$$

the thickness of the longitudinal windings on the cylindrical section being t_l.

In a similar way we can relate the thickness of the helical windings at

any point with the distance of that point from the axis and the angle of wind

$$t_{\theta_e} = t_\theta \left(\frac{D}{2r}\right)\left(\frac{\cos\theta}{\cos\theta_e}\right) \tag{108}$$

The conditions of equilibrium given in Equations 83 and 84 apply equally to an area on the end closures and therefore, if we change the suffices, we obtain

$$t_e S_{le} = t_{le} S + t_{\theta_e} S \cos^2\theta_e \tag{109}$$

$$t_e S_{te} = t_{te} S + t_{\theta_e} S \sin^2\theta_e \tag{110}$$

Using these basic equations, we can eliminate S_{le}, S_{te}, t_{le}, t_{θ_e}, and S to give the following equation governing the end closure geometry

$$\frac{R_t}{R_l} = 2 - \frac{\sin^2\theta_e\left(\dfrac{\cos\theta}{\cos\theta_e}\right)}{\dfrac{t_l}{t_\theta} + \cos\theta\cos\theta_e} \tag{111}$$

This equation gives a relationship between R_t and R_l for different conditions of winding on the cylindrical section. This is a very definite curve and is predictable from the thickness of each form of winding and the angle of winding. If there are no longitudinal windings, the end closure will be defined by the equation

$$\frac{R_t}{R_l} = 2 - \tan^2\theta_e \tag{112}$$

This is a simple geometrical relationship and can readily be traced for any curvature. It is not always possible, however, to put the windings down in a way to keep the pattern described mathematically; therefore it is important to have some method of determining the stress if the windings are not put on properly. This can be done by combining Equations 104, 106, 107, and 109 to give

$$S = \frac{pr^2}{\cos A(D)(t_l + t_\theta\cos\theta\cos\theta_e)} \tag{113}$$

If then there is any discrepancy in the winding pattern, this equation will show what the stress in the fibers might be. It should, naturally, be less than the designed value of S in the cylindrical portion of the vessel.

Equation 112 gives the ideal curvature for the end closure if the helix angle is certain and the filament can be put down as designed. This is often very difficult and is usually restricted to patterns that do not lend themselves to simple development. For instance, if a winding is put down in one plane, such as in the Vermont Ball Winding System, whose winding head is shown in Figure 7.28, the θ_e of the end closure varies with the distance of the winding from the axis. It changes from θ at the edge of the cylindrical section to 90 degrees where the winding is tangential to the edge of the end opening. Here the curvature of the end closure must be computed with these varying

Figur 7.28 Winding machine applying planar windings. (Courtesy of Vermont Ball Winding.)

conditions; it is necessary to wind an initial specimen and observe the angle and then redesign the end shape with this information. This gives a shape on the second try which may be used for making fine and consistent test specimens. Such a winding is often referred to as a planar winding because its windings are put on in one plane.

When windings are put on in a plane they tend to draw out of that plane into a geodesic curve, which is the shortest distance along the surface of a curve. This is the natural curve which a cord in tension will assume on a surface and ideally one in which a winding should be wound for maximum efficiency. This form of winding would demand a different end-closure geometry from that of the planar winding but it would again fit in with Equation 112. In fact, when the deviation of a planar winding end profile from that of a geodesic is determined by tensing a string against the surface, as shown in the profile in Figure 7.28, there is little detectable deviation. The difficulties of putting down a geodesic curve will often be outweighed by the simplicity of the planar application.

Theoretically, the condition for a winding to be put down in a geodesic curve is (22)

$$r \sin \theta_e = \text{constant} \tag{114}$$

Since the filament will be faired in with the cylindrical portion, the constant can be evaluated, so that

$$r \sin \theta_e = \frac{D}{2} \sin \theta \tag{115}$$

which is the condition at the edge of the end closure.

On substituting this in Equation 112 for the profile of the end closure

$$\frac{R_t}{R_l} = 2 - \left[\left(\frac{2r}{D \sin \theta}\right)^2 - 1\right]^{-1/2} \tag{116}$$

This again is a distinct curve that can be evaluated to give a profile. This curve requires a specific curvature to be applied to the filament while it is being wound over the end closure and is more complicated in application than the planar winding in Figure 7.28.

The technique for adjusting the profiles to fit the equations when the filaments are to be laid down by a moving eye held above the surface of the mandrel must be developed by a combination of theoretical and practical work on the machine that will be used for winding. The idiosyncrasies of the machine itself and its mode of guidance must

be taken into account. The first step is to make a full-sized mandrel with a reasonable end-closure geometry that will be nearly what is needed—a hemisphere will be satisfactory for the purpose. This closure geometry will then be modified in accord with the observations. The filaments should next be wound over these approximate ends so that θ_e for points at different distances, r, from the axis of the mandrel can be computed.

With the values of θ_e plot R_t/R_l can be plotted from Equation 112 for different values of r. With this information the profile can be plotted directly and allowances made for the changing values by a stepwise procedure. To illustrate this procedure, consider a pressure vessel whose angle of helix over the cylindrical portion is 10° and whose overall diameter is 20 inches.

At the edge of the cylindrical portion $\theta_e = 10°$, $R_{tl} = 10$ inches, but from Equation 112, $(R_t/R_l)_l = 2 - \tan^2 10° = 1.97$ or $(R_l)_l = 5.08$ inches. Draw in the first step as in Figure 7.29. The first step should be small, but assuming from the graph of θ_e that the next value of θ_e is 15°, at step 2, $R_{tl} = 9.98$ inches $(R_t/R_l)_2 = 2 - \tan^2 15° = 1.93$ or $R_{l_2} = 5.17$ inches. This process can be repeated until the central hole is reached, and the profile will be one stage better than the original half sphere. This profile should now be cut on an end closure and tried in the machine to give a new series of values for θ_e and the process repeated to give a still more accurate profile.

This repetitive process is necessary for any practical machine other than one that lays down planar windings; the errors from theory introduced by the height of the winding head from the surface of the mandrel will be an incalculable term in any theoretical study. The technique described is rapid and accurate, and the first profile computed will be in almost complete agreement with theory.

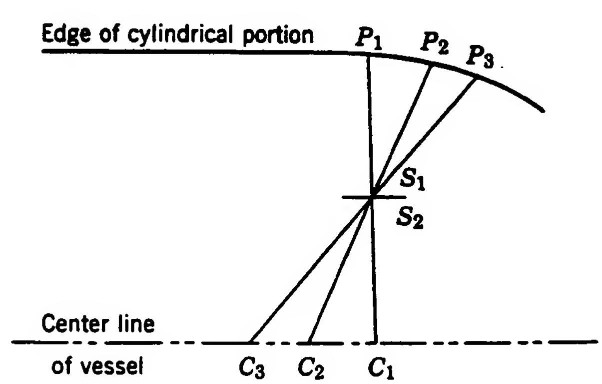


Figure 7.29 Graphical procedure for stepwise estimation of end closure design (21).

Various combinations of helical, longitudinal, and hoop windings are possible in the cylindrical section of an internal pressure vessel designed for optimum conditions. The thickness of the vessel will be independent of the combination of the windings and can be computed from the diameter needed, the inherent strength of the glass, and the pressure that the vessel is designed to hold. The angle of wind will determine the other necessary thicknesses.

End-closure geometry can be predicted theoretically but must be adjusted to the form of winding that is to be put on and the winding technique used. The simplest form is the planar winding, in which the windings are applied so that each turn lies in a distinct plane. Another predictable shape is the geodesic winding, in which the filament lies in a curved plane so that the tension will not pull it out of line on the end profile. When the filament is put down by a guide that is moved from end to end of the vessel by a screw or other device, the profile of the end must be determined by trial and error to satisfy the profile equation for the particular motion used. All these profiles must be checked in practice and are peculiar to the machine used, unless planar winding is the only kind employed.

LARGE CASE DESIGN

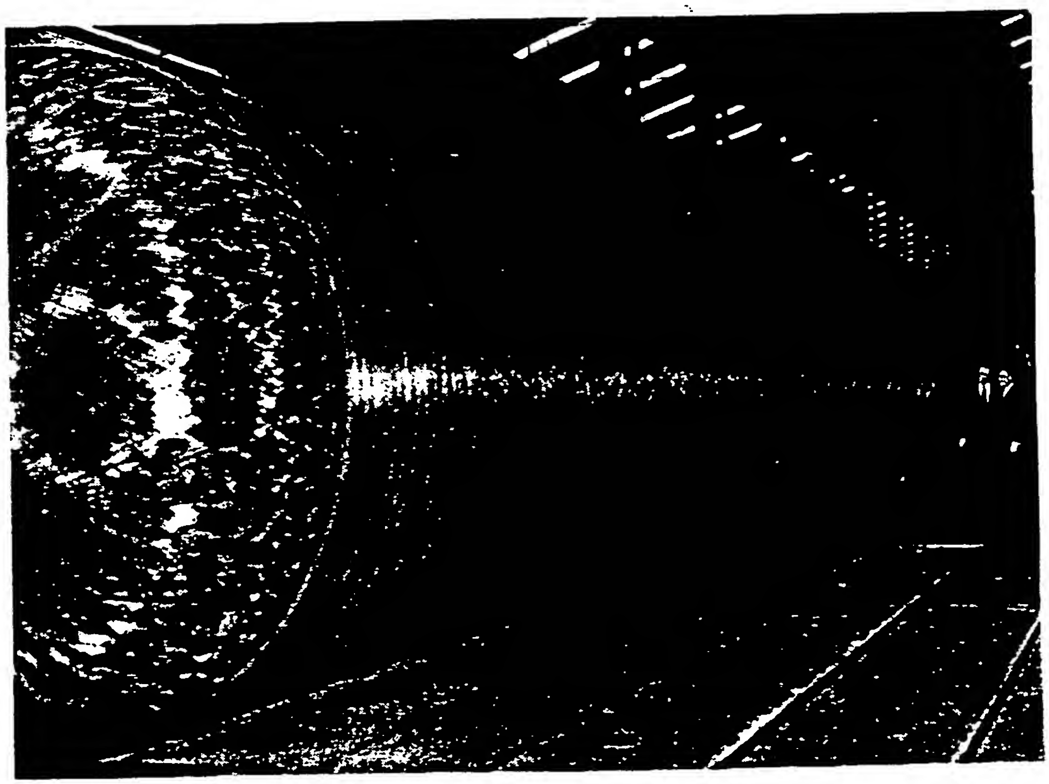
Much emphasis is currently placed on developing large segmented cases, and the potential use of these cases appears to be very great. In order to realize reduction in fabrication time, increase reliability, reduction in weight, and cost savings from the use of fiber glass in these applications, a lightweight reliable mechanical joint is required. However, the low bearing and shear strengths of fiber glass resin laminates force the engineer to develop unique joint designs (designs encompassing metal to fiber glass or even fiber glass to fiber glass laminates, capable of developing the full strength of the basic fiber glass structure) (23).

Two concepts for segmenting motor cases will be reviewed; the circumferentially segmented and the longitudinally segmented (or modular) concepts. The emphasis is placed on the design and fabrication techniques for pinned joints in domes and cylinders, utilizing thin high-strength steel strips, bonded between the filament-wound fiber glass layers. Also of importance are the use of an elastomeric material in areas of high shear stresses and the modular concept with its special dome contour and fabrication problems.

Two of the more promising concepts or segmenting filament-wound rocket motor cases are the circumferentially segmented concept and

the longitudinally segmented concept, hereafter referred to as the segmented and modular concepts. The segmented case consists of a forward closure, aft closure, and cylindrical center segments connected by lightweight pinned joints. The modular case is an assembly of several modules, composed of filaments oriented on meridianal lines, which form portions of the forward and aft closures and are mechanically fastened to the forward and aft polar rings. The outer cylinder is of prefabricated hoop rings or circumferential windings.

It is realized that the present analyses used to determine basic wall thickness and case geometry will have to be modified to efficiently utilize the strength of the glass filaments when the case wall thicknesses approach and exceed 1 inch. The method of analysis for very large cases and the development testing programs to verify these analyses are presently being studied. It is to be assumed for this review that present methods of analysis are applicable with a related decrease in usable glass strength and, therefore, only the unique features of the two segmented concepts will be discussed. These features are the design of a lightweight joint for segmented cases; the



Figur 7.30 Visible geometric design of 9-foot-diameter by 55-foot-long railway tank. (C urtesy of Black, Sivalls and Bryson, Inc.)

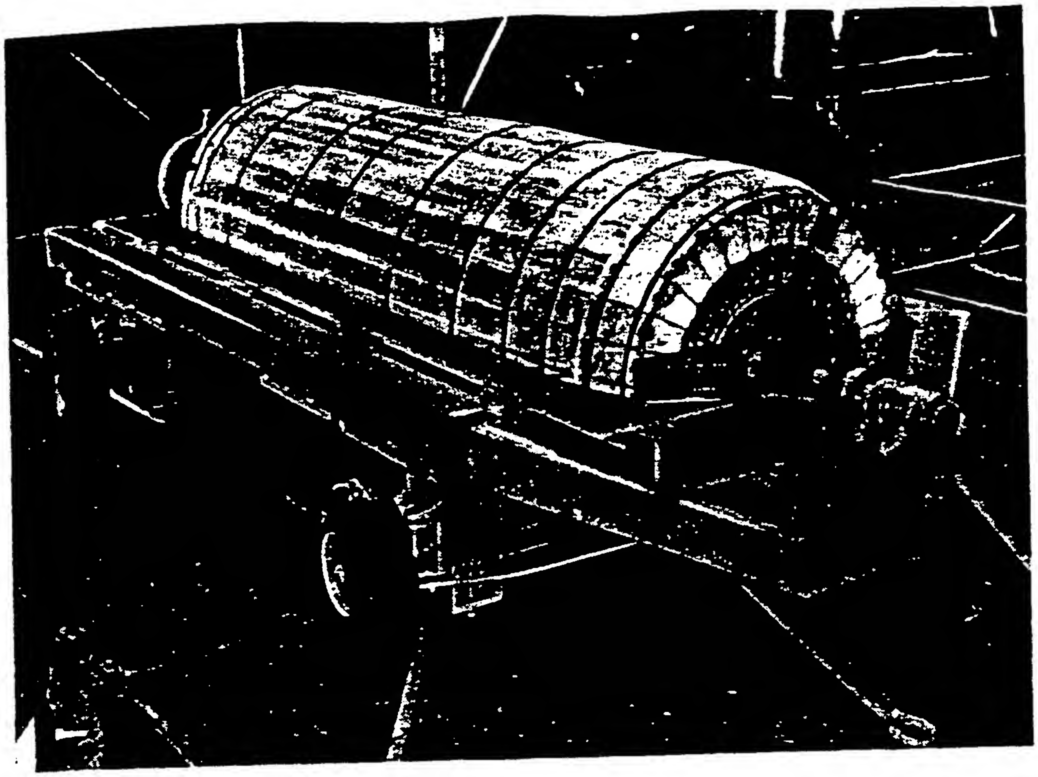


Figure 7.31 View of aluminum segmented mandrel in the plaster sweep fixture, just prior to the application of a final sweep coat of plaster to bring up the mandrel to the final O.D. required for the application of the forward, aft, and cylindrical insulation. (Courtesy of Aerojet-General Corp.)

module design, fabrication, and assembly; the methods of attaching hoop rings to the assembled modules; and the skirt attachment for modular cases.

SEGMENTED CASE CONCEPT

The design of the basic case cylinder and closures can be accomplished by the same methods employed for monolithic cases. The primary concern in the segmented concept is the design of a lightweight joint. Since mechanically fastened joints are necessarily thicker than the case, they offer greater restraint to radial growth than does the case. This differential growth results in discontinuity forces, which necessitate a weight penalty in design. If the joints of a filament-wound case are reinforced with steel, the differential growth is further exaggerated by the contrast in elastic moduli (10.5×10^6 psi for glass and 30×10^6 psi for steel). However, this may be minimized by using the filaments' abilities to orient themselves. If the joint is

located at the tangent point of the closure and the cylinder, the closure contour and its filament path can be readily calculated to obtain the radial growth required to eliminate discontinuity forces. The case growth can be made to coincide with the joint growth by using the critical wrapping angle principle; that is, as the wrapping angle exceeds 54¾ degrees, the ratio of hoop strain to helical strain decreases.

Rocket motor performance requirements for most applications dictate joint locations and winding parameters. Thiokol Chemical Corporation, Brigham City, Utah, has worked toward developing a joint concept that can be designed to have the same radial restraint as the case. At the present time, all trade-off studies indicate that the clevis-type joint is the most efficient concept. The clevis joint is composed of thin, high-strength steel shims, laminated between the helical layers of the case with the hoop windings wound outside the joint region. It should be noted that the hoop and helical windings are interspersed in the case and that the hoop layers terminate at the start of the shims. The interspersing of hoop and helical windings requires an external skirt attachment.

Experience has indicated that under the influence of high longitudinal strain in the case and compressive strain in the skirt, a pure resin bond between skirt and case is unsatisfactory, or at best unreliable. To circumvent this problem, Thiokol uses a layer of elastomeric material between skirt and case to reduce shear stresses and improve reliability. This concept has proved successful on Minuteman size rocket motor cases. The analysis is performed using shear lag principles to derive equations describing the shear stresses introduced by both conditions of loading.

The filament winding of the segments can be accomplished by conventional equipment and techniques; however, specialized equipment and/or techniques will be required for the joints and skirt attachments. Items that will require special consideration for joint fabrication are:

1. Shim placement and alignment.
2. Shim to glass bond.
3. Spacer and filler for clevis.
4. Joint buckling during cure because of differential thermal expansion.
5. Machining of holes.
6. Interchangeability of segments.

Probably the simplest method of shim alignment is to use aligning pins that extend from the mandrel. Two pins per shim would be required. The pins are located at a sufficient distance from the trim line to eliminate band distortion in the joint area.

The clevis spacer must exhibit dimensional stability during fabrication and cure. Washout sand castings are an efficient solution. The filler is either an epoxy-microballoon or epoxy-glass mat composite. To eliminate bulking during cure, several layers of hoop windings are wrapped over the joint area. A teflon film separates these windings from the joint so that they can be cut away after cure.

The machining of pin holes can be a costly and time-consuming operation if proper consideration is not given to steel shim strength versus machinability and cost during the design phase. In many applications this could warrant an extensive trade-off study. Good results have been achieved with two tools: trepanning and double-fluted carbide drills.

The requirements of interchangeability impose high cost because of the tolerance control necessary. Thiokol's work with clevis joints for steel cases has shown that these tolerances can be relaxed somewhat if a tapered pin is used. These pins are inserted with a small force so that when loading begins and throughout loading all pins will carry their share of the load.

Modular Case Design

The modular concept (longitudinally segmented fiber glass rocket motor case) consists of two basic elements, the module and the hoop ring.

The modules are preformed and precured, with all fibers oriented in the longitudinal direction, extending beyond the tangent lines to form either or both domes. The domes described by these modules consist of only longitudinal fibers, hence, their contours must describe a "no-hoop load dome."

The circumferential strength of the cylindrical section is supplied by hoop rings, which are fitted over the assembled modules. These hoop rings also consist of precured and preformed unidirectional fibers. Often, it is possible to fabricate skirts as an integral part of the hoop rings.

The tension load in a module can be supported in different joint design. One approach is transferred by shear into the steel foil (which is integrally wrapped with the module); the foil, in turn, carries the load into a bolted joint connecting the adapter ring. The analysis is basically similar to that previously discussed in the segmented joint.

The hoop-module bond can be designed with rubber acting as the elastomeric material. The bond must be of sufficient thickness and strength to withstand the longitudinal growth of modules. However, the tensile strength of the hoops in this direction is low, and its strength

approaches that of the resin only. Hence, resin crazing or cracking in the hoops is necessary; the design problem becomes one of controlling and equalizing this hoop crazing.

The steps required to fabricate a modular (longitudinal) vessel are:

1. Wrapping hoops.
2. Wrapping modules.
3. Wrapping skirts.
4. Assembly of modules.
5. Placing of hoops around modules.
6. Completion and sealing of liner.
7. Adhesive bonding.

The hoop rings are wrapped on a cylindrical mandrel with either a prepreg material or a wet wrap. With either method, the segmented case is ideal for good quality control and inspection; the individual components are not immediately assembled. Time can be provided for testing and, if required, rejecting of any part. Such flexibility is obviously not possible in standard filament-winding methods. Another advantage of the versatility found in the segmented concepts is the ease with which it may be vacuum-bagged to control resin content.

The modules are wrapped in pairs on a special mandrel, tightly controlled in tolerances and contours. Steel sheets designed to carry the bearing loads in the joint areas are laminated between the glass. Any necessary reinforcement or filler cloths are added in conjunction with the steel laminates. When the loading permits, the skirts are wrapped as an integral part of a hoop ring instead of using the elastomeric bond previously discussed.

To combine the components into a case, the parts (modules, polar boss, and, if applicable, the skirts) are assembled, braced, and drilled. Then the hoop rings are slipped over the assembled modules. Finally, after the entire vessel is assembled and the liner is sealed, it is completed by internal pressurization while the bond (hoop-to-module) cures.

DATA

Properties

Physical properties of filament-wound structures have been studied since the inception of these types of configurations. Typical of new developments, differences of opinion exist regarding the practicability

and usefulness of old data. The more common values which have been established and are presently being used will be reviewed in this section. Table 7.6 provides basic properties of different materials used in pressure vessels.

Ultimate strengths in hoop have been demonstrated in the production of glass filament-epoxy-wound pressure vessels greater than 150,000 psi. These vessels yield a specific strength of over 1.8×10^6 inches. The primary load is carried by the glass fibers. Tensile strength in the fiber alone averages 320,000 psi. This type of structure is generally made up of 80 per cent glass by weight and 20 per cent resin. It represents a volume ratio of 65 per cent glass (Figure 7.4).

When a combination of low helical windings and circular windings is used, it has been determined from actual burst tests that the circular windings are up to 25 per cent stronger at failure than the helical fibers. This general condition is the result of imperfect packing of the helical fibers as they cross each other at the ends of the ovaloid ends. Another factor is the changes in radius of curvature from the tangency point to the end. For practical reasons, it is best to design structures under the assumption that all fibers are operating at the same stress and that uniform density exists.

Continuous fibers have been produced from glass with considerably higher tensile strength-to-weight ratios than have been produced from metals (24). The availability of such fibers has proved important in the development of rocket motor cases and they have marked cost advantages over metals. Multiple openings, such as are required for four nozzle motors and thrust-reverser ports, impose penalties on filament-wound structures. The penalties consist primarily of additional materials, either in the form of reinforcement where filaments are cut or in the form of extra thickness because of altered filament patterns to circumvent the openings. Because of the versatility of filament winding, the minimum requirements for these structures can be met at the expense of more weight than would be required theoretically. Despite this added weight, the overall total weight still produces an overall maximum efficiency of strength to weight when compared to other materials.

Rocket motor cases made of E-glass rovings with a glass tensile strength of 200,000 to 250,000 psi have at least a theoretical net glass hoop strength of 170,000 to 210,000 psi. If an allowance is made for the plastic content and for imperfections in winding or handling basic materials, these structures may display only 80,000 to 130,000 psi in hoop tensile strength.

The fibers can carry loads only in their axial directions. A part of

Tabl 7.6 Properties of Internal Pressure Vessel Materials

Material	Ultimate Hoop (Tensile) Strength, psi	Density, pounds/cubic inch	Specific Strength [1], 10^6 inch	Thermal Conductivity [2]	Tensile Modulus of Elasticity, 10^6 psi	Compr s-siv Strength, psi
Glass-Resin [3] (Unidirectional)	130,000 to 170,000	0.077	1.6–2.1	2.0–5.0	6.0–9.0	70,000 t 175,000
Glass-Resin (Bidirectional)	60,000	0.072	0.7	2.0–5.0	2.0–3.5	40,000 t 60,000
Steel Wire-Resin (Bidirectional)	150,000	0.166	1.0	—	12	—
Titanium (H m geneous)	50,000	0.163	0.9	—	16.5	135,000
Steel (Homogeneous)	280,000	0.280	0.9	314	30.0	—
Aluminum (Homogeneous)	80,000	0.097	0.8	1,416	10.0	40,000
Magn sium (H mogeneous)	32,000	0.064	0.5	—	—	—

[1] Specific strength equals ultimate tensile strength/density (approx.).
[2] BTU/hour/°F/square foot/inch
[3] Int rlaminar shear strength = 6,000 to 8,000 psi (parallel to laminations); 20,000 psi (perpendicular to laminations)
Axial bearing strength = 20,000 to 40,000 psi
Compressi n strength = 50,000 to 70,000 psi

the total number of fibers in a composite must be oriented in different directions. In the typical rocket motor cylindrical case, a 2-to-1 biaxial stress relationship exists from the hoop to the longitudinal directions. The maximum possible glass in the axial direction is only one third that of the fiber material. In the hoop direction, as many as two thirds of the total fibers can be used.

Lack of recognition of the relationship between the biaxial tensile strengths of composite cases and strengths of the filaments employed accounts for some ambiguous comparisons between properties of fiber structures and monolithic structures when they are loaded biaxially.

For the commercial type E-glass fiber roving, the modulus of elasticity can reach 12.5×10^6 psi. In a cylindrical case, the modulus of elasticity in the hoop direction can reach 9×10^6 psi. The axial modulus of the composite generally ranges from 3 to 6×10^6 psi.

Imperfections. Imperfections in filament-wound vessels will generally cause reduction in strength and performance. Various design factors ranging from 1.1 to 12.5 are presently being used in order to account for the reduced performance. Imperfections or reduction in strength can be attributed to various conditions, for example, variation in resin content, imperfections in winding, broken fibers due to handling, non-uniformity or imperfect winding tension on the fibers, etc.

Cylindrical glass filament-wound pressure vessels have been tested to destruction at an ultimate strength of 150,000 psi. This particular shape provides a specific strength of 2.1×10^6 inches. With the same unidirectional strength value, a spherical shape can theoretically be fabricated with the same density. The specific strength for this sphere is 1.6×10^6 inches. Based on this comparison, it appears that the cylinder is more efficient than the sphere. Imperfect packing and limitation on providing the most efficient helical wind in the sphere result in this correlation.

In the isotensoid structure (or oblated spheroid) spheric strength values of approximately 2.1×10^6 inches have been developed. In addition, the roving ends do not include excessive resin or imperfect alignment of fibers (13). These factors contribute to the increased specific strength.

In some of the present rocket motor missile applications the design requirement for a composite case is 80,000 psi hoop strength. This value is based on the use of a safety factor of 1.25. The relatively low stress level primarily reflects the low capabilities of a structure in which cut fibers occur as at multiple port openings (1). In order to insure a high degree of reliability, a large number of tests are conducted on finished cases.

As these special programs progress, the test results will probably show a consistently higher stress level than the 80,000 psi based on design parameters. This would permit the reduction of the number of tests required. To cite an example, in one missile system, a part is accelerated to 260 G's. To insure 99.5 per cent confidence limits, only 1 failure in 10,000 can be tolerated. If, however, the filament-wound part could be improved to withstand a 3,000-G loading without any changes in later dimensions, it would then be possible for 300 failures to occur in 10,000 trials and the confidence level at 2,600 G's would still be 99.5 per cent.

In addition to conducting destructive testing of a large number of motor cases to establish satisfactory confidence levels, it is necessary to proof-test all cases before acceptance by the military. This is done hydrostatically, usually at a level which is at 80 per cent of the design burst pressure. The practice of using repeated cycle burst test has practically been eliminated, since this type of evaluation tends to considerably reduce the ultimate burst level.

NOL Ring Test. Ring test results based on the standard NOL dimensions as well as slight modifications produce tensile strength values ranging from 200,000 to 280,000 psi (25). When tests are conducted after specimens are immersed twelve hours in boiling water, reductions in strength of up to 50 per cent can occur (26). Tension moduli of elasticity (dry) vary from 7 to 9×10^6 psi for E-glass. All values are for composite stress.

Dry ultimate flexural strengths range from 190,000 to 230,000 psi. Using the 12-hour boil exposure, wet strengths ranged from 60,000 to 180,000 psi. Correspondingly low values exist; namely, the wet 180,000-psi value exists for 230,000 psi.

Compressive test results have ranged from 170,000 to 185,000 psi in strength and 7.1 to 7.5×10^6 psi in modulus.

Horizontal shear-strength data range from 10,000 to 12,000 psi. Using a 6-hour boil conditioner, shear values ranged from 8,000 to 9,000 psi.

The exposure to boiling water is used purposely to cause damage within the laminar structure. This procedure permits evaluation of the effect of glass finishes or coupling agents used to improve glass-resin bond. With glass-woven fabric-reinforced plastic laminates, a 2-hour boiling condition is sufficient to cause breakdown. However, with the filament-wound structure, the 12-hour boiling condition is required to show degradation of tensile and flexural properties. The 12-hour period is probably too severe a condition for flexural tests. Only a 6-hour boil period is used with the shear specimens.

The preceding ring test results are based principally on glass roving epoxy systems. Resin content was approximately 20 per cent by weight. The higher-strength values are generally obtainable with rings fabricated of single-end glass.

Buckling. The modulus of elasticity (E) in a filament-wound composite is not uniform. It depends on the winding geometry with major components in the circumferential and longitudinal directions. In a wound cylinder with a 2:1 ratio E-hoop can be 5 to 6×10^6 psi and E-longitudinal from 4 to 5×10^6 psi. A pure hoop winding with unidirectional properties the E-hoop can reach 8 to 9×10^6 psi.

These composite E figures are based on using conventional E-glass which has a specific modulus of 10 to 12×10^6 psi with density of 2.54. The new high-modulus glasses with specific values of 15 to 20×10^6 psi and density of 2.84 provides increased modulus/density properties. Other properties can be reduced but reduction is slight. Major modulus increases occur when using steel wire (30×10^6 psi) which produces a composite E of 18×10^6 psi in unidirectional layup.

Modulus values have a direct effect on buckling loads. In the following equation for calculating bending moments the critical buckling bending moment varies directly with the modulus and square of the wall thickness:

$$M = K \frac{E}{1 - u^2} (rt^2) \tag{117}$$

where M = bending moment
K = 1.0 constant
r = radius
u = Poisson ratio (.1 to .3)—dependent on materials of construction, resin content, and winding geometry
t = wall thickness

As an example the critical buckling bending moment results in cylinder wall thickness to vary. When density is taken into account the glass-filament unit is most efficient even though it has the thickest wall. These factors are summarized in Table 7.7.

Stress-Strain Relationships. Reinforced plastic stress-strain curves for tension, compression, flexure, and shear generally follow a straight line. Deviation from the straight line generally occurs at 90 per cent of failure (27).

When closely examining typical glass fiber-resin laminates, the stress-strain curves tend to have two straight sections, a primary level and a secondary level (Figure 7.32).

Tabl 7.7 Relative Relationship of Critical Bending Moment (Buckling), Cylinder Wall Thickness and Case Weight

Material	Moment, 10^6, pound-inch	Thick-ness, inch	Density, pound/cubic inch	Modulus of Elasticity, 10^6, psi	Case Weight Ratio Rate *	Ratio of Manufacturing Cost	Ratio of Tooling Cost
Glass fiber-	8	0.30	0.077	4	1.00	1	1
epoxy	50	0.65	0.077	4	1.00	1	1
Steel wire-	8	0.20	0.135	9	1.15	1	1
epoxy	50	0.40	0.135	9	1.15	1	1
Titanium	8	0.15	0.165	16	1.02	3	6
	50	0.33	0.165	16	1.02	3	6
Steel	8	0.12	0.278	30	1.31	2	6
	50	0.28	0.278	30	1.31	2	6

* Cylinder case weight ratio at a fixed bending moment is the relationship of critical bending moment to total weight of cylinders.

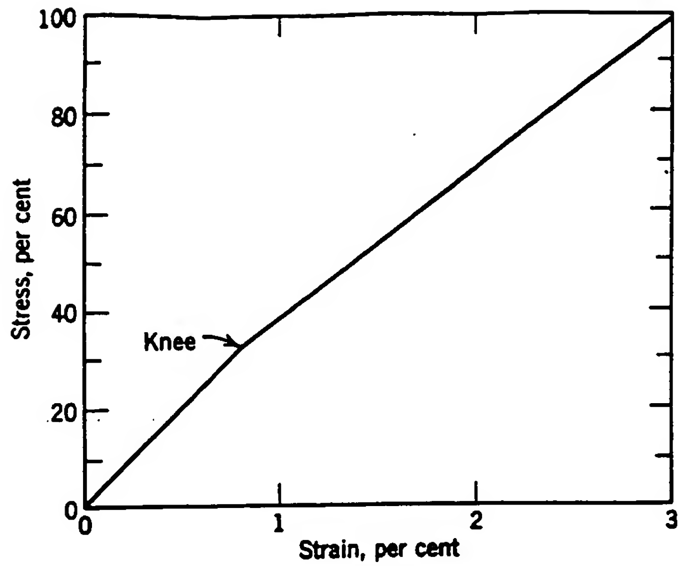


Figure 7.32 Stress-strain diagram of filament-wound pressure cylinder; note that cylinder wall is biaxially loaded hydrostatically.

This particular phenomenon has been extensively studied in glass fabric reinforced plastics. However, this dual characteristic tends to change or disappear after loading to a stress beyond the initial proportional limit. Preloading to a value between the initial and secondary proportional limits tends to eliminate the initial slope. The net result is a stress-strain proportion equivalent to the secondary line.

The initial yield generally occurs at 30 per cent of ultimate load resulting in a two-step curve. When using polyester resins, it is difficult to develop this two-step curve. Available data shows that the epoxy-resin laminates have a more pronounced two-step curve than do polyester resin systems.

The effects of preloading epoxy laminates appear to be similar to those observed for polyester laminates. The exception is that the final modulus of elasticity for the epoxy laminates is substantially greater than the secondary modulus obtained in the first loading. Regardless of the resin system used, the secondary modulus of elasticity is ordinarily reported.

The stress-strain curve for the filament-wound pressure cylinder is based on internal hydrostatic pressure loading. The typical glass-epoxy laminate dual characteristic of glass fabric laminates is reproduced. It is predicted that with improved fabricating techniques and controlling prestressed fiber conditions during fabrication, the

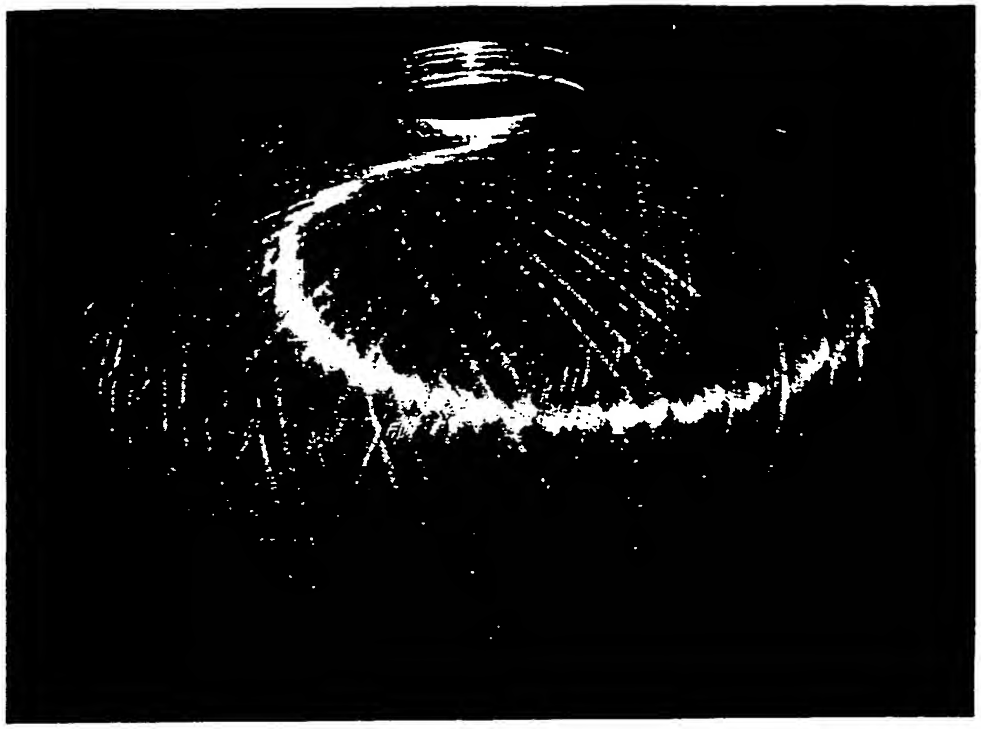


Figure 7.33 Ultra-light-wound rocket case; the actual stress level in the glass fibers at the moment of fracture under internal pressure is 320,000 psi. (Courtesy of Narmco Research and Development.)

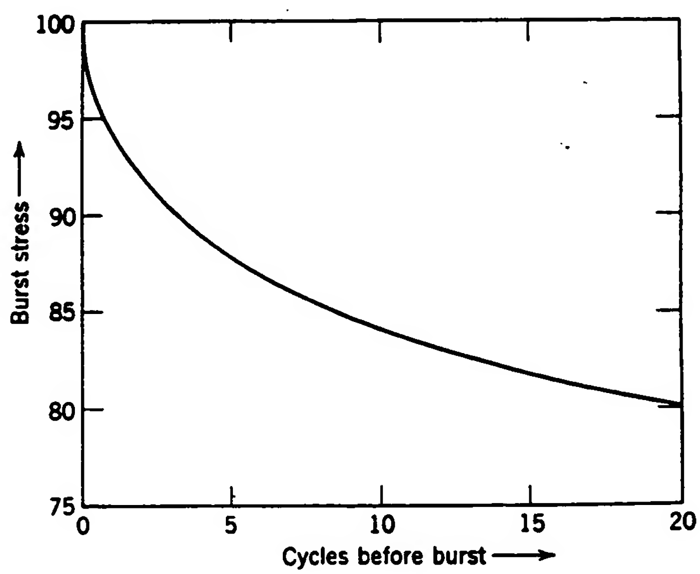


Figure 7.34 Repeated-stress effect on pressure cylinders (11).

dual line will be eliminated or drastically reduced. Based on experience with glass fabric-epoxy resin systems, the future filament-wound structure will also have an increased modulus of elasticity value.

Repeated Stress Effects. Glass filament-epoxy resin filament wound vessels have been subjected to repeated internal pressure cycles. The design of solid-fuel rocket motor cases generally requires not more than five pressure cycles (Figure 7.34).

Variation in Resin Content. The amount of resin applied to glass before the actual layup generally varies. Variations also occur when pressure is applied during the winding operation. Tensile and flexural strength properties tend to decrease with increasing resin content. The tensile breaking loads (pounds per inch of width) tend to remain constant within a reasonable resin variation (Figure 7.4).

This indicates that the apparent effect of resin content on tensile strength of a laminate is primarily a result of differences in laminate thickness. An increase in laminating pressure generally results in decrease in resin content and decrease in the percentage of voids. The data in Table 7.8 typifies this condition.

Relatively low strains in the composite materials can lead to high strains, and hence to stresses in the resin itself. This occurs because the glass filaments, which are stronger than the resin, resist deformation, and thus the small amount of resin in the composite is highly strained in comparison to the composite itself.

Table 7.8 Resin Content versus Tensile Strength

Resin Content, Per Cent by Weight	Tensile Strength, psi
18	200,000
20	192,000
25	175,000
30	150,000
35	138,000

Note: For correct comparison of composite efficiency, the strength values should be related to glass fiber volume (wh r resin sp cific gravity is 1.2)

$$r \qquad \frac{\text{c mposit strength}}{\text{\% glass volume}}$$

The stresses and strains in the resin are important, for they can initiate resin crazing and failure in glass-resin interface bond. Maximum stresses and strains in the resin increase as the spacing between adjacent filaments becomes small with respect to the diameter of the filaments (4).

Crazing. Resin crazing is generally defined as the formation of fine cracks in the filament-wound structure during load application. Investigators have conducted internal hydrostatic pressurization tests (28) and have noticed that definite changes occur in the slope of the stress-strain curve. The initial modulus value is significantly higher than the secondary apparent modulus. It appears that with this slope change, the crazing occurs and cracking sounds are heard. Preliminary analysis indicates that a potential increase of approximately 30 per cent in ultimate chamber pressure could be achieved by elimination of crazing without degrading the elastic properties (29).

During hydrotesting, crazing within the laminar construction is observed to occur before the formation of surface crazing. Test data indicates that crazing is related principally to the strain of the structure rather than to a particular stress level. The crazing is attributed to tensile elongation in the direction normal to the direction of the craze crack.

Cryogenic Effects. The strength properties and moduli of glass fiber reinforced plastics tend to increase with decreasing temperature down to minus 400°F. The amount of increase varies with both the property involved and the resin type. Increases occur in tension, compression, and flexure with the different resin systems; that is, epoxy, polyester, silicone, or melamine. An increase also occurs in fatigue and impact properties (27). At the lower temperatures, increases may reach 50 per cent above room-temperature properties. If the properties do not increase, they will at least be equal to room temperature properties.

General useful temperature ranges for various materials are as follows:

1. Organics
   - (a) Reinforced plastics — −400 to 1000°F
   - (b) Non-structural plastics — −400 to 2000°F
2. Metals
   - (a) Stainless steel — 0 t 2000°F
   - (b) Refractory metals — 0 to 6000°F
3. Nonmetals
   - (a) Ceramics — 0 to 6000°F
   - (b) Graphit s — 0 to 6000°F

An important and useful design characteristic for glass-filament-wound structures is its strength properties in cryogenic environment. Metal composites or homogeneous units will tend to lose strength or become brittle at these same temperatures.

EXTERNAL PRESSURE VESSELS

In order to develop an efficient strength-to-weight ratio in underwater structures, increased compressive properties are desirable (30). Glass reinforced plastics are generally lower in compression than they are in tension because of the nature of internal failure. Tensile failure is a purely mechanical failure of the glass filament, whereas compression failure is a combination of material failure and local instability of the fiber in its resin (31).

The unidirectional compressive strength value generally used by the designer for glass-epoxy filament-wound structures is 70,000 psi. A value being used by some designers is 100,000 psi, and average values as high as 120,000 psi have been reported based on laboratory results (32). Unidirectional compressive strength results have been reported in the laboratory as high as 250,000 psi (33). Increases in available compressive strength values are being made possible through modified resin systems (34), through advances in the state of the art for applying fibers in relatively perfect alignment, through studies conducted to increase the diameter of the fiber, and through the production of differently shaped fibers.

Hydrospace Vehicles

Deep submergence pressure hulls of glass filament are being considered. The glass fiber structures have been recognized as having certain advantages over other types of materials for this application. Programs presently being conducted in this area are as follows (35).

- A. Basic Studies
  - 1. Mechanism of Failure
    - (*a*) Material Laboratory, New York Navy Yard
    - (*b*) Naval Research Laboratory
  - 2. Resin-Glass Interface
    - (*a*) Debell and Richardson, Inc.
    - (*b*) Material Laboratory, New York Navy Yard
  - 3. Mechanism of Water Diffusion
    - (*a*) Battelle Memorial Institute

4. Polymer Structure
   (a) Naval Research Laboratory

B. Materials
   1. Resin Matrix
      (a) Aerojet-General Corporation
   2. Reinforcements
      (a) Coarse Glass Monofilaments
          Narmco R & D
      (b) Methods for Improving Shear Characteristics
          Naval Ordnance Laboratory
   3. Properties of Thick Laminates
      Aerojet-General Corporation
   4. General Evaluation of Resins
      Reinforcements and Methods of Attachment
      Material Laboratory, New York Navy Yard

C. Tests
   1. Investigation of Test Methods, New York Navy Yard
   2. Fatigue and Creep
      (a) Mono- and BI-Axial
          Armour Research Foundation
      (b) Large Panels
          Material Laboratory, New York Navy Yard

D. Design, Repair, and Modification
   1. David Taylor Model Basin:
      (a) Stiffened and Unstiffened Model Tests
      (b) Composite Metal-Plastic Model Tests
      (c) Design Details
      (d) Design of Filament-Wound Laminates

E. Fabrication, Quality Control, and Inspection
   1. Fabrication of Thick Laminates
      Aerojet-General Corporation
   2. Production Variables
      Quality Control and Nondestructive Test
      Material Laboratory, New York Navy Yard

Development programs are being directed to increase compressive strength properties and set up design stress allowables based on conditions such as effects of cyclic fatigue and long-term exposure to deep submergence pressures.

The equation presently being used by investigators to determine bursting pressures produced by external loads is based on the thin-wall shell elastic buckling theory, which is actually applicable to isotropic materials (36).

$$P = \frac{2.42E}{(1 - \mu^2)^{3/4}} \times \frac{(t/D)^{3/2}}{L/D - 0.45(t/D)^{1/2}} \tag{118}$$

where E = modulus of elasticity
μ = Poisson's ratio
P = burst pressure
L = length
D = mean diameter
t = wall thickness

Investigators who have applied this equation have determined that it provides rather close agreement of the filament-wound structures with the conventional sheet materials. The value used for Poisson's ratio ranged from 0.10 to 0.15.

References

1. A. M. Shibley, H. L. Peritt, and M. Eig, SPI Annual Preprint, p. 6A (February 1962).
2. J. T. Holfeditz, SPI Annual Preprint, p. 7C (February 1963).
3. J. E. Bell, SAMPE *Report*, p. 205 (March 1961).
4. J. C. Schulz, SPI Annual Preprint, p. 7D (February 1963).
5. Walter Kiddie and Co., Inc., Brochure A-12R1-2M-4-60YP (1960).
6. A. M. Shibley, H. L. Peritt, and M. Eig, Army PLASTEC Report 10 (May 1962).
7. L. B. Greszczuk, Douglas Aircraft, Inc., SM-41543 (29 March 1962).
8. C. C. DeHaven, "Pressure Vessel with Min. Hoop Stresses," Hercules Powder Co. (1958).
9. O. R. Burggraf and H. U. Schuerch, NASA Technical Note D-1920 (May 1963).
10. M. Eig and H. Peritt, Army Picatinny Report 3027 (March 1963).
11. R. E. Young, University of California Course (July 1961).
12. Narmco Research and Development Reiease on NASA Pumpkin (December 1961).
13. B. Levenetz, Narmco Research and Development Report W. O. No. 090-031 (December 1961).
14. J. D. Marketos, AIAA Report 2916-63 (April 1963).
15. R. E. Young, 17th Annual Meeting of JANAF-ARPA-NASA, pp. 2–53 (May 1961).
16. A. L. Courtney and W. E. Werts, SAMPE Meeting Report, p. 147 (March 1961).
17. W. F. Freiberger, *J. Aeronautical Sciences*, **24**(11), p. 847 (November 1957).
18. B. Duft, Narmco Research and Development Report, "Role of Composite Construction in Primary Missile Structures" (31 May 1961).
19. Aerojet-General Corporation Report on Glass-Filament-Reinforced Hom - geneous Chambers (15 April 1963).
20. E. L. Strauss, *Materials in Design Engineering*, 1, 86 (February 1963).

21. J. O. Outwater, *Modern Plastics*, p. 135 (March 1963).
22. C. F. Baeschlin, *Lehrbuch der Geodesic*, Orell Fussli Verlag, Zurich (1948).
23. J. R. Hinchman and W. D. Humphrey, AIAA Report 2918-62 (April 1963).
24. R. J. Runck and B. W. King, Battelle Memorial Institute OTS PB 171629 (6 June 1961).
25. P. W. Erickson, H. A. Perry, and F. R. Barnet, SAMPE *Meeting Report*, p. 246 (March 1960).
26. B. L. Duft and N. Brink, Narmco Research and Development Report, Role of Glass-Reinforced Plastics in Underwater Studies (1962).
27. Plastics for Flight Vehicles, Part I, *Reinforced Plastics*, Military Handbook MIL-HDBK-17, Armed Forces Supply Support Center, Washington, D.C. (5 November 1959).
28. G. Epstein and W. Bandaruk, SAMPE *Symposium*, Section 16 (June 1963).
29. F. J. McGarry and Y. Stavsky, WADD-TR-60-746 (June 1962).
30. J. E. Buhl and J. G. Pulos, SAMPE *Meeting Report*, p. 325 (March 1961).
31. B. L. Duft and N. Brink, Undersea Technology, Plastic Pressure Hull (July/August 1961).
32. W. R. Graner, J. E. Buhl, and J. G. Pulos, BuShip Report 1524 (August 1961).
33. S. P. Prosen, T. G. Roskos, and F. R. Pflederer, SPI Annual Preprint, p. 9D (February 1963).
34. N. Fried, SPI Annual Preprint, p. 9A (February 1963).
35. W. R. Graner, SPI Annual Preprint, p. 2A (February 1963).
36. D. F. Windenburg and C. Trilling, BuShip Report 385 (July 1934).

8 Test Methods

One of the major problems in compiling design data for any engineering material is that of correlating the results of standard tests with performance of the material in its final shape. Filament-wound structures offer a unique problem in this regard. Established methods for developing reinforced plastic data generally involve the use of flat laminated specimens. These types of test are not always directly applicable in wound structures.

In the present era many new materials are being developed for diversified applications encompassing parts for industrial, commercial, aerospace, and underwater consumption. All this could represent the Materials Age. Filament winding fits into this category. As winding materials multiply and as their applications pose even more severe engineering problems, inherently materials testing multiples and becomes more sophisticated.

Because of the special nature of both the materials and their application, new types of tests have been developed. These tests have been used simultaneously in the laboratory and the production or quality control areas.

SPECIFICATIONS

The filaments in wound structures are primarily load-bearing members. They can be designed to be stressed only in tension when internal pressures are applied or in compression when external hydro-

static pressures are applied. A variety of other types of loads are encountered. Different standard tests and new special tests are used. Principal sources of tests are contained in ASTM and government publications (1, 2, and 3). Various tests have been developed in order to produce meaningful test results (4). In certain applications the process of developing these new methods has actually become more complex than the process of developing end items.

At the present time, the only existing specifications for filament-wound vessels or structures concern the performance of the end item after it is fabricated (5). Both military and industrial specifications of this type exist. The joint military organizations (Air Force, Army, and Navy) are presently in the process of directing a specification MIL-P-27327 to establish requirements for standard test specimens, standard test fixtures, and standard methods of tests on filament-wound plastics so that results from multiple sources can be correlated.

NOL RING TEST

The NOL (Naval Ordnance Laboratory) ring test is most often used by the industry, since it is relatively inexpensive to run and yields reproducible data (6). This test was originally developed in order to study the effect of various chemical finishes on glass roving as related to the strength properties of the reinforced plastics. The

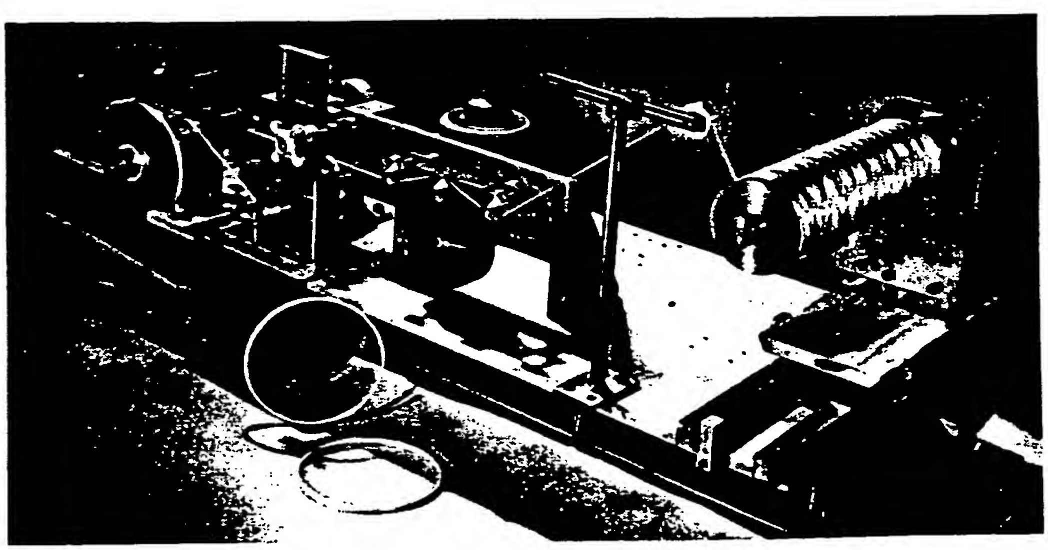


Figure 8.1 NOL ring-winding apparatus provides orientation, tension control, and roving impregnation for fabrication of ring specimens. (Courtesy of Aerojet-General Corp.)

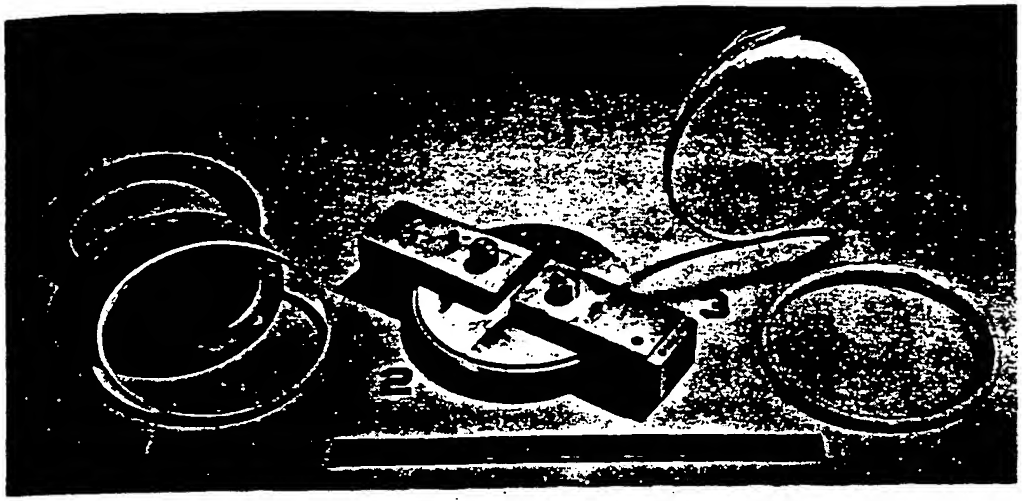


Figure 8.2 NOL ring specimens: (1) after cure, (2) ready for split tensile test, and (3) after test. (Courtesy of Aerojet-General Corp.)

ring test still provides this type of study; however, it is now predominantly considered as a sufficiently reproducible testing technique.

NOL cured rings can be tested by different techniques in order to obtain properties such as tensile strength and modulus, flexural strength and modulus, compressive strength, and fatigue strength. Various size rings can be made up and tested. The standardized ring measures 5.75 inches internal diameter, 0.250 inches wide, and 0.125 inches thick. This ring is fabricated under controlled conditions which typify the fabricating procedure, for example, temperature, time, fiber tension, method of applying resin to filament, and angle of wind applicable to size of ring.

Split-Ring Tension Test

As shown in Figure 8.3, a ring can be mechanically tested in conventional testing machines. In this figure, electrically heated elements are located on opposite sides of the ring so that elevated temperature tests can be conducted. The NOL ring fixture can also be placed in an oven to conduct relatively temperature tests at the lower range. Basically, this test produces results with limited use. Flexural stress of an unknown magnitude is superimposed on the tensile stress at the points of separation as the discs move apart. This results in a changing radius of curvature at these points. Frictional forces between the discs and specimen result in nonuniform loading. The specimens always tend to break at one of the two separating points. The tension modulus of elasticity cannot be obtained with this test.

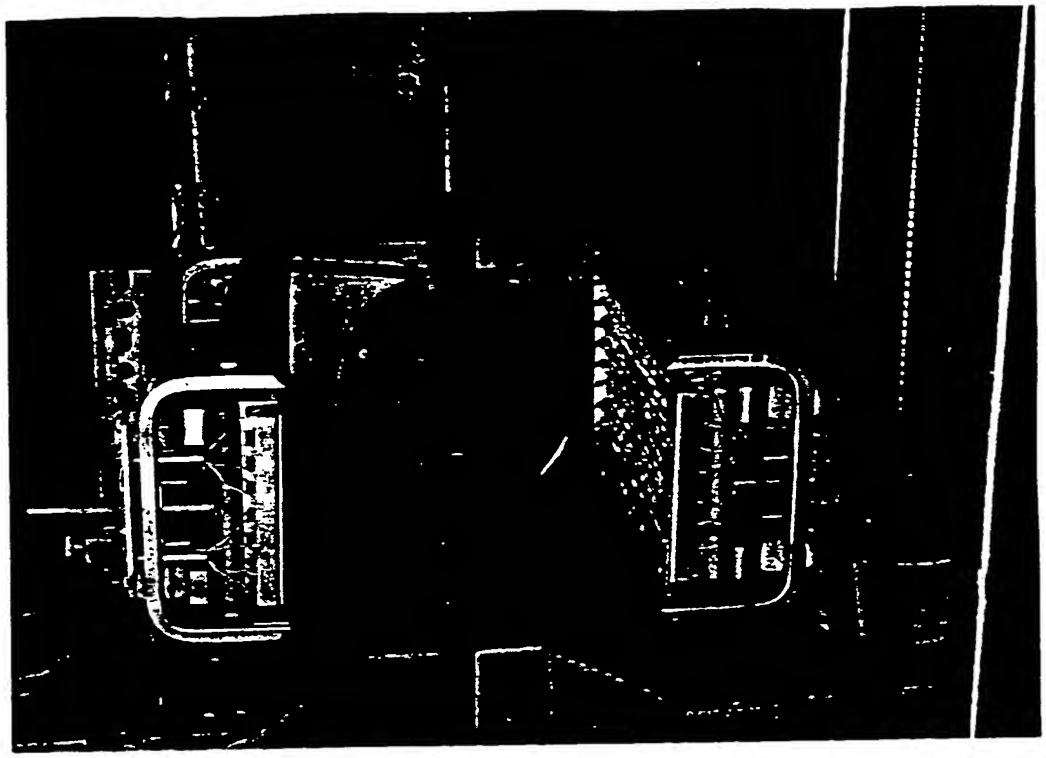


Figure 8.3 Elevated temperature set-up for conducting split disk NOL ring test. (Courtesy of Narmco Research and Development.)

Hydraulic Tension Ring Test

This test utilizes the same type of sample as the NOL ring. The ring is placed in a closed fixture, as shown in Figure 8.4. A test machine loads a piston which forces oil into the center area of the ring. The pressurized oil bears against the inner surface of the test ring until failure occurs. A rubber obturator ring provides the means whereby the oil pressure is exerted only on the inside of the ring. Figure 8.5 shows typical test specimens after the burst test.

The area of the piston is exactly 1 square inch, so that the oil psi is read directly on the test machine. As the test ring dilates under stress, one of the end bands, connected to an extensometer, retracts and thus gives a measure of strain as a function of stress. A stress-strain plot is automatically recorded, from which Young's modulus is calculated.

Inherent problems in this particular system involve the difficulty in setting up other than ambient test conditions for testing. Tooling for this test is relatively complex and expensive. However, this technique eliminates the changing radius of curvature and friction forces

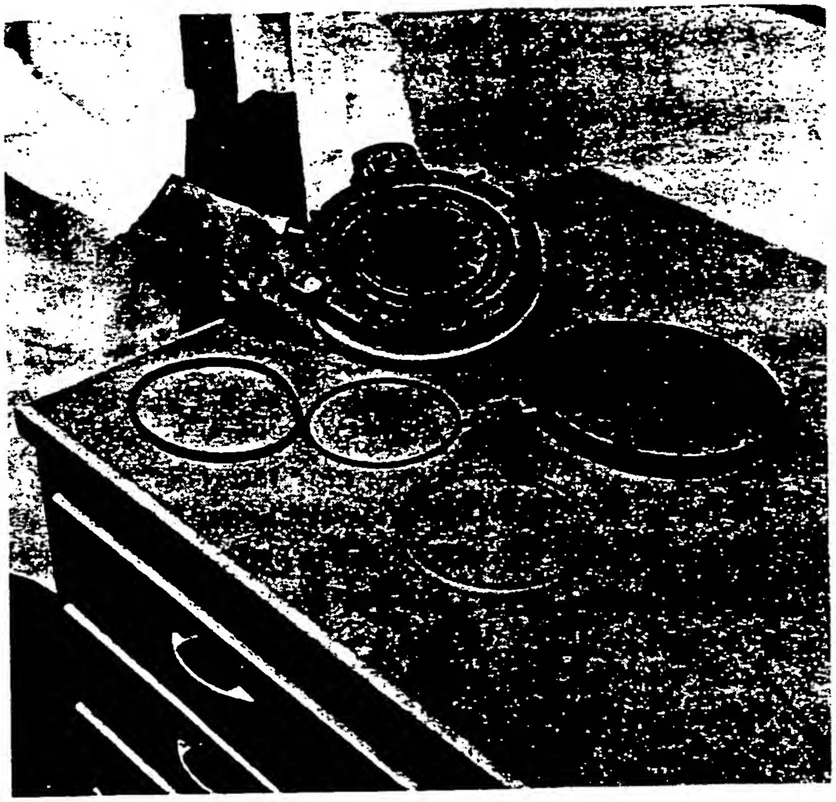


Figure 8.4 Hydraulic testing unit for evaluating NOL rings. Load is transferred hydraulically rather than mechanically. (Courtesy of Narmco Research and Development.)

Figure 8.5 NOL rings after tensile burst test. (Courtesy of Narmco Research and Development.)

developed in a split-ring tension test. It now gives greater reliability both in hoop tensile values and in modulus. Actual values run approximately 30 per cent higher for the hydraulic burst than for the tensile pull. Some laboratories continue to use the split disc method for testing, but the trend is to use the hydraulic burst method. It is a useful quality control device for laboratory or production comparison of properties.

Interlaminar Shear Test

The inside and outside dimensions of this type of test specimen are similar to the specimen as listed in the previous section, except that the length is approximately 2 inches. Two square grooves, each ¼ inch in width, are machined near the center section of the tube. One groove is machined from the outside and the other groove is machined from the inside. Both are cut to the midsection of the wall thickness. The distance between the two grooves is approximately ¼ inch.

A test machine applies load in the axial direction with the crosshead feed not to exceed 0.050 inch per minute. If the modulus of elasticity in shear or per cent elongation properties is to be determined, an accurate deflectometer or dial indicator can be used to measure the overhead travel. The general minimum requirement of 10,000 psi is being used for the ultimate interlaminar shear-strength value.

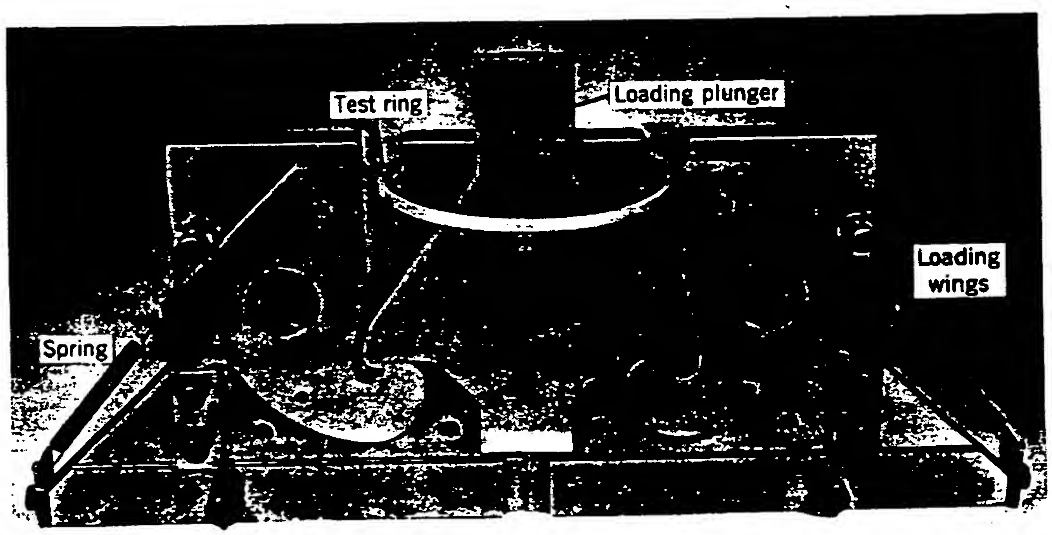


Figure 8.6 Section of compression model test fixture. (Courtesy of A. O. Smith Corp.)

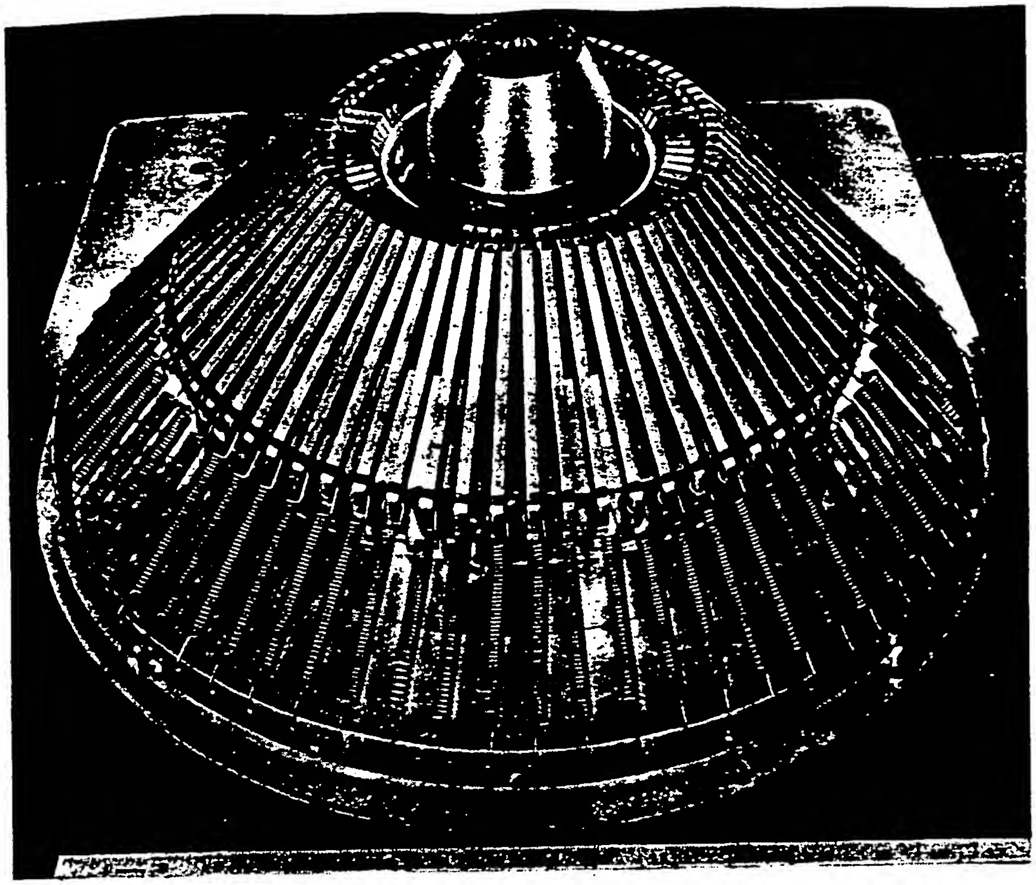


Figure 8.7 NOL compression test fixture with cover removed. (Courtesy of A. O. Smith Corp.)

Compressive Test

The NOL ring has been subjected to various different tensile and shear loading devices. A compressive test fixture has been developed, with a failure mechanism providing true compression on the same type NOL specimen (7). The design of the fixture eliminates the ring from buckling failure or elastic stability failure.

The mechanical action of the fixture is shown in Figure 8.6. This figure shows basically two wings which exert uniform and controlled load. As shown in Figure 8.7, the complete fixture is made up of 72 identical loading wings. Uniform radial deformation occurs on the ring when the central loading plunger moves in a standard testing machine. By recording plunger vertical motion, stress-strain curves can be plotted during the test run. Test results on HTS glass roving–epoxy resin rings have ranged from 170,000 to 185,000 psi in strength and 7.1 to 7.5 $\times$ 10^6 psi in modulus.

C MPRESSIVE TESTS

Axial

The test which is gradually being adopted in various specifications involves the use of a filament-wound tube measuring 2.998 inches inside diameter, 1 inch or less in wall thickness, and approximately 3 inches in length. The end surfaces of the tube are parallel within 0.005 inch per inch. The tubular test specimens are accurately centered in an annular grooved platen pin. Approximately ¼ inch of each end is potted in the groove with epoxy resin. A suitable resin system for potting involves 100 parts by weight of "Dowex" epoxy resin #332 and 22 parts with Sonita 41 agent.

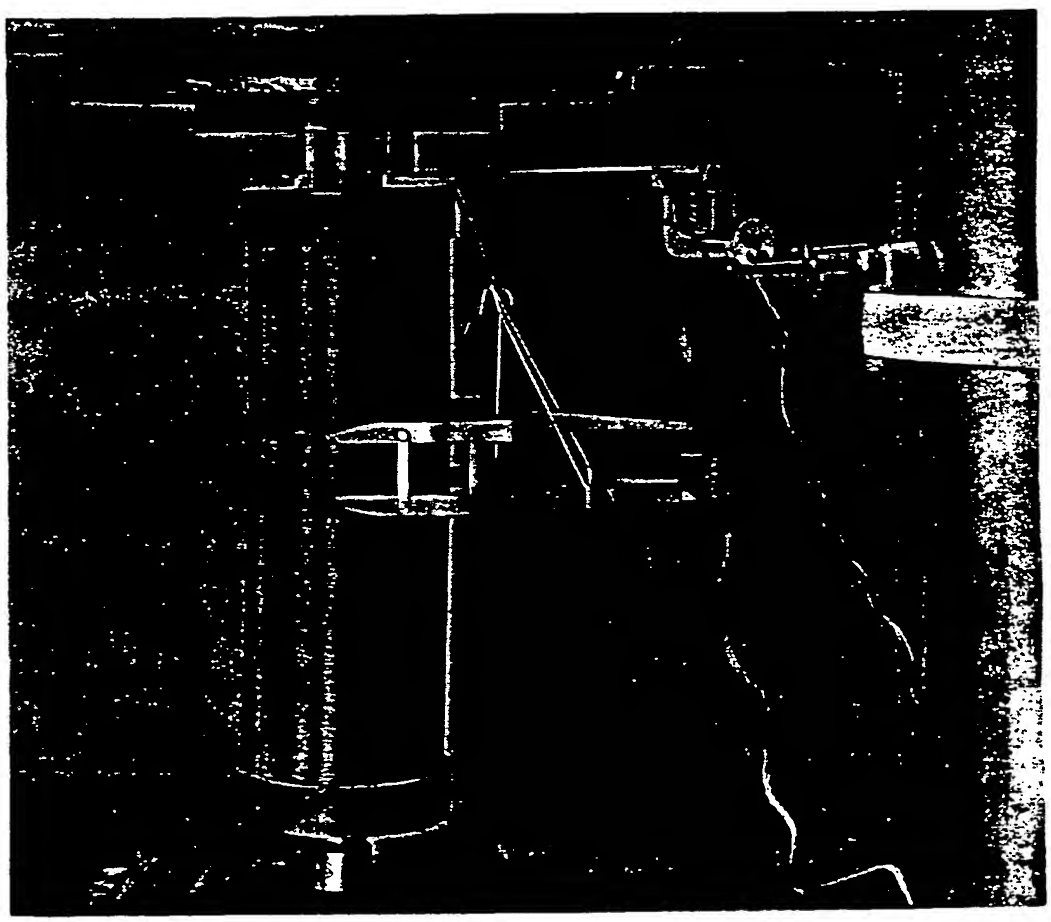


Figure 8.8 Filament-wound tube buckling under axial compression. (Courtesy of Hughes Aircraft Co.)

An electrical strain gauge is mounted in the center of the test specimen in order to measure the compressive strain in the axial direction (Figure 8.8). The rate of feed of the test machine is 0.010 inch per minute. Ultimate strength in compression is calculated by dividing the maximum load sustained by the original cross-sectional area of the specimen. For this size specimen, the tentative minimum requirement for potential specifications is 50,000 psi ultimate axial compressive strength.

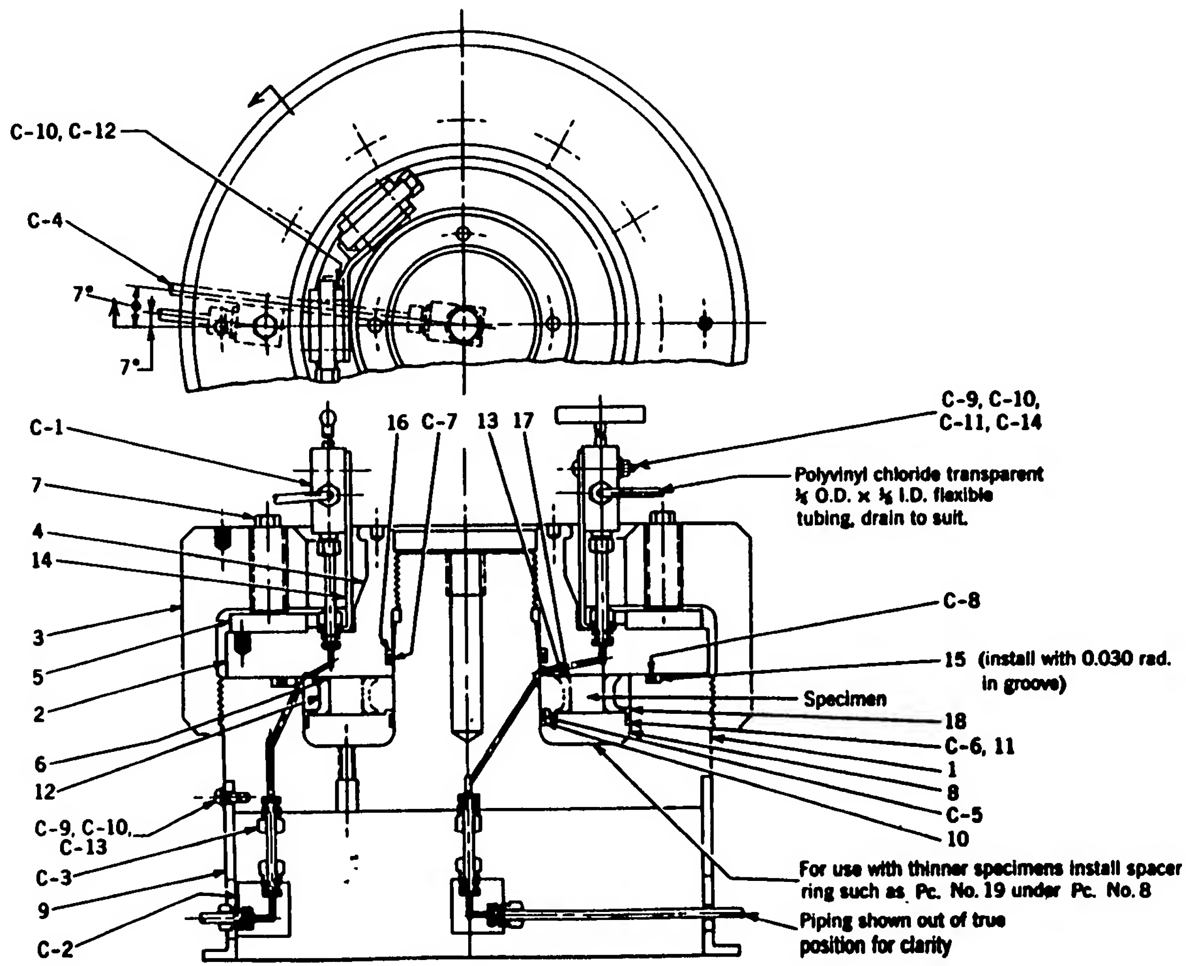
External Hydrostatic Ring

The Naval Applied Sciences Laboratory (8) has developed an apparatus to enable the evaluation of the compressive and tensile properties of wound specimens by applying external and internal hydrostatic radial pressure, respectively. Thick-walled steel rings have been tested for the purpose of calibrating the apparatus.

In Figure 8.9 an assembly drawing of the hydrostatic test fixture is shown. This dual-function design permits a certain degree of versatility in that specimens of circular cross section, up to 1 inch in axial length, can be tested in compression or tension with hydrostatic pressures up to 25,000 psi. Valid stress-strain curves can be plotted.

In conducting a test with external hydrostatic pressure, the specimen is placed in the fixture as shown in the drawing, the sealing ring (12) is set in place, and the fixture is closed. Water is introduced through the fittings shown at the lower left, and air is bled out through the valve at the upper left. Hydrostatic pressure is then built up with a 30,000 psi Sprague pump. Strain gages may be mounted on the inner wall of the specimen and the leads brought out through the port at the lower right. Specimens of varying axial length may be accommodated by the use of spacer rings, as indicated on the drawing. Internal pressure tests are conducted in a similar manner, with the sealing ring inside the specimen and the strain gages on the outer circumference, by bleeding and loading through the appropriate alternative channels.

The apparatus just described was designed to be used for the determination of the compressive strength and modulus of filament-wound rings or sections of cylinders. In addition, it was intended to use the equipment for studies of creep, stress-rupture, and cyclic fatigue at different stress levels. At the time the design of the apparatus was conceived, there was a dearth of information on the compressive strength of filament-wound composites. The commonly ac-



PART NO	NAME	MATERIAL AND SPEC
1	BODY	STEEL
2	TOP PLATE	
3	COVER NUT	
4	PRESSURE NUT	
5	WASHER RING	
6	BACK-UP RING	TEFLON
7	BOLT, HEX. HEAD	STEEL
8	GLAND COLLAR	STEEL
9	STAND	ALUM
10	BACK-UP RING	TEFLON
11	BACK-UP RING	TEFLON
12	SEALING RING	RUBBER
13	SEALING RING	RUBBER
14	BRACKET	STEEL
15	BACK-UP RING	TEFLON
16	BACK-UP RING	
17	BACK-UP RING	
18	RING	STEEL
C-1	VALVE	COMM
C-2	ELBOW	
C-3	CONNECTOR	
C-4	TUBING ¼ O.D. × $\frac{3}{16}$ I.D.	
C-5	"O" RING	RUBBER
C-6	"O" RING	
C-7	"O" RING	
C-8	"O" RING	
C-9	WASHER, FLAT	STEEL
C-10	WASHER, LOCK	
C-11	NUT, HEX.	
C-12	MACHINE SCREW	
C-13	MACHINE SCREW	
C-14	MACHINE SCREW	
19	SPACER RING	STEEL
20	WRENCH, SPANNER	STEEL

Figure 8.9 Assembly drawing of hydrostatic test fixture to conduct either compressi n or tensile tests (8).

cepted value for a representative material was 70,000 psi. Assuming this value for ultimate compressive strength, a modulus in compression of 6 to 8 $\times$ 10^6 psi, and an arbitrarily selected outer diameter of 8 inches, the design of a typical ring specimen, which would fail at yield, was developed.

For a modulus of 7 $\times$ 10^6 psi, a ring with an 8-inch outer diameter and a wall thickness of about 0.76 would be expected to fail at a hydrostatic pressure of 12,300 psi by yielding, that is, with the stress at the inner wall reaching the ultimate strength of 70,000 psi. Considering the possibility of developing materials of higher strength, it was finally decided to design an apparatus with a maximum working pressure of 25,000 psi. With this maximum working pressure, it may be calculated that an 8-inch O.D. ring, with a modulus of 7 $\times$ 10^6 psi, and of sufficient wall thickness to preclude failure by elastic buckling, could be stressed up to 116,000 psi at the inner wall. Thus, materials with this ultimate compressive strength (116,000 psi) could, theoretically, be tested.

HYDROSTATIC BURST TEST

Different size specimens are used for this particular test. Basically, a parallel-wound or angle-oriented wound tube with a length-to-diameter ratio of 1 to 4 is used. End closures can be made integral parts of the ends of the tube. With this type of test specimen, when internal hydrostatic pressure is applied, the tube will expand and elongate. In some applications the end closures may be made secure in relation to the tube and also internally held in position. A tie bar is used to prevent the end closures from expanding during the test. This type of specimen basically provides only expansion of the circumference.

A more popular burst test involves a specimen that can be permitted to expand in both the circumferential and longitudinal directions. One type specimen has an inside diameter of 3.170 inches, a wall thickness of .062 inch $\pm$.010 inch, and a length of 24 inches. Within approximately 2 inches of each end of the tube, a build-up of material exists. Rubber plugs and end plates are in turn fitted at each end. These plates are then clamped to the built-up material sections. Hydrostatic pressure is applied through one of the end plates.

Circumferential and longitudinal strain gages are bonded to the specimen within the center of the test section. Pressure is applied by a hydrostatic test machine equipped with a device to continuously record pressure. The pressure is applied at a rate of 100 to 500

pounds per square inch gage (psig) per second until specimen failure.

This type of burst test is being considered for use in a government specification MIL-P-27327 entitled "Plastic Materials, Glass Fiber Base, Filament Wound." The specification is being prepared to standardize testing techniques. It is to be specifically applicable for parts fabricated with glass reinforcement in order to develop a high strength-to-weight ratio. The high strength-to-weight ratio is to result from the selective orientation of the glass fibers during fabrication to produce an approximately equal unidirectional tensile load in each fiber, making a highly efficient structure.

Tentative minimum test requirements are as follows (where secant modulus of elasticity is obtained by dividing the stress at 70 per cent of ultimate strength by the corresponding strain):

Ultimate hoop tensile strength	139,260 psi
Ultimate longitudinal tensile strength	69,600 psi
Hoop modulus of elasticity (secant)	5×10^6 psi
Longitudinal modulus of elasticity (secant)	2.5×10^6 psi

CYCLIC FATIGUE: PRESSURE TESTS

Filament-wound vessels and pipe are subjected to cyclic internal pressure testing. Specific tests have been set up to provide expedient and meaningful methods of determining acceptance of end items (9). Procedures have been set up to detect failures and also provide a means for evaluating the characteristics of either short- or long-term fluid-carrying capacity.

When evaluating the performance of a reinforced plastic pipe, the end use of the pipe must be considered. If a pipe is going to be subjected to frequent on-off pressure cycles, it is important that these be considered in the evaluation. In general, burst tests cannot be used to indicate long life-expectancy of a fluid-carrying pipe.

Cyclic testing of either plastic or metal pipe has become a useful tool in laboratory evaluation of the fluid-carrying capacity. The cyclic tests can also be used to conduct quality control on raw materials and the manufacturing processing variables.

The generally accepted test specimen for cyclic fatigue evaluation is similar to the burst test specimen, as previously described, using an inside diameter of 3.17 inches. The rate of pressurization and depressurization is 400 to 500 psig per second. The maximum pressure applied is that pressure causing a hoop stress of 66,120 to 69,600 psi inclusive in the test specimen. An efficiently wound specimen can

withstand at least 1,000 cycles. The static pressure test specimen is similar to the fatigue specimen. An internal hydrostatic pressure is produced with a hoop stress of 62,120 to 69,600 psi. An acceptable and efficient wound tube will maintain this fixed pressure for at least 1,000 hours.

The following discussion is a summary from Fred R. Pflederer of A. O. Smith Corporation (9) regarding cyclic pressure testing of reinforced plastic pipe, and it is described as a method that gives a realistic evaluation of the long-term characteristics of the fluid-carrying capacity of the pipe. Equipment that has been developed for this test is described in detail along with special instrumentation for failure detection. Experiments that show the effect different maximum pressures have on cycles to failure are discussed.

Investigators have shown that burst tests are indicative of fast loading only and have conducted long-term steady-pressure tests to determine life-expectancy of the pipe. When such results are determined, acceleration factors must be applied to account for variables not included in the test. Experience with thin-wall glass reinforced epoxy pipe has shown that cycling the pressure in a pipe creates a more rapid failure than a steady pressure does. This is probably caused by some fatiguing condition. It would be expected that pressure cycling would create some acceleration factor in all reinforced plastic pipe, but the data presented is only directly applicable to the Red Thread line of pipe manufactured by A. O. Smith Corporation.

During the early stages of cyclic pressure testing it was found that equipment components were being tested as much or more than the pipe specimens. Salt water was and still is being used as the testing fluid, and no high-pressure pumps were found to give satisfactory performance in handling this fluid. Normal corrosion-resistant solenoid operated valves would freeze up after a short period of operation. After several years of equipment development work, a trouble-free system has been achieved and is shown schematically in Figures 8.10 and 8.11.

In Figure 8.10, a standard oil pump is used and a four-way solenoid operated valve diverts the oil alternately to two pressure legs. A simple electric pulsator operates the solenoid of the four-way valve, and the maximum pressure in each leg is controlled independently by separate manually set pressure relief valves. The pressurizing fluid is transferred to salt water in an accumulator which has either a piston or a membrane as the fluid separator. The test specimens are coupled to a manifold directly from the accumulator. A check valve on the rear side of the specimen will close as the pressure in the

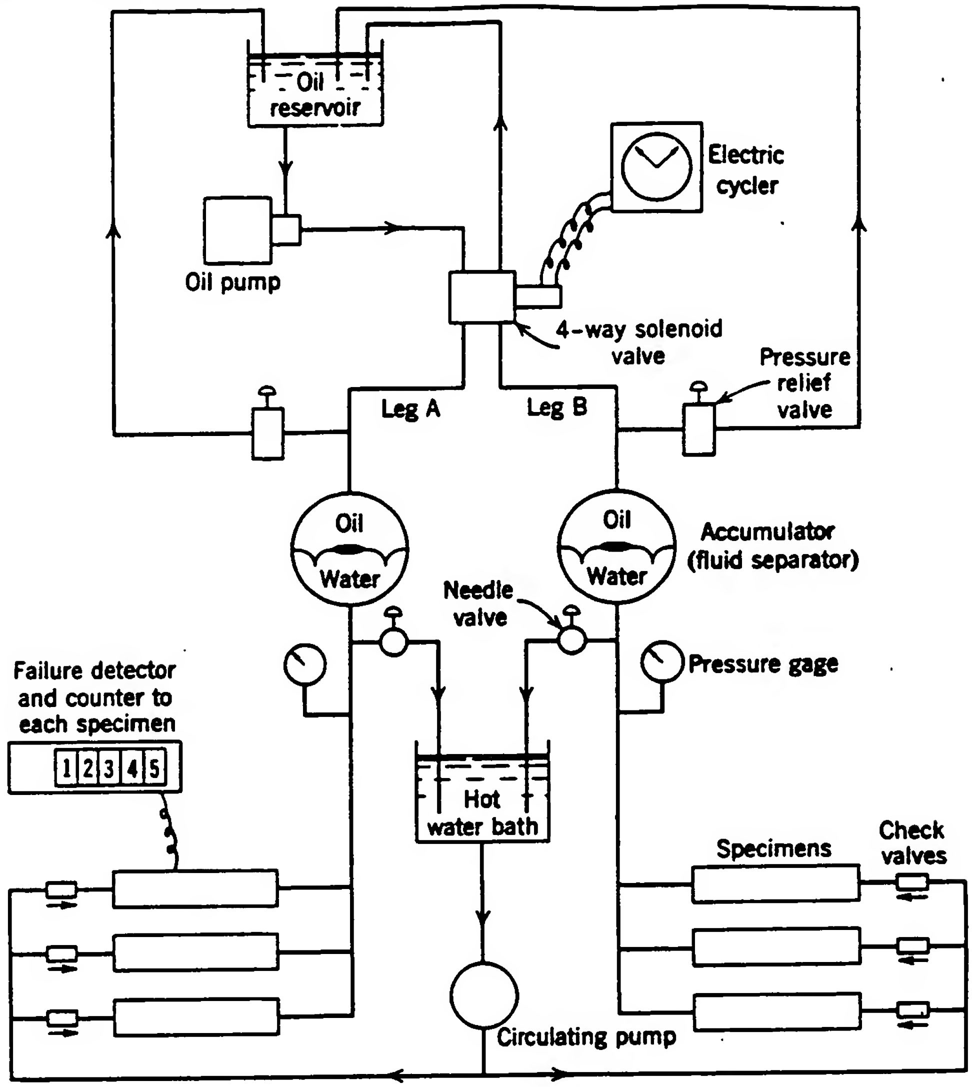


Figure 8.10 Schematic of cyclic pressure pipe test equipment. (Courtesy of A. O. Smith Corp.)

specimen is raised. The remaining piping shown on the figure is for the purpose of obtaining a desired temperature of the fluid in the test specimen. A needle valve is placed in a line leading from the water side of the accumulator to the hot water bath. In operation this valve is open slightly, and a small quantity of water flows constantly through it. During the off portion of the pressure cycle, the oil side of the accumulator is exhausted to the oil reservoir and a circulating pump (45 psi) recharges the water side of the accumulator with the lost water. This recharged water comes from the thermostatically controlled hot water bath, and by circulating through the test specimen

it maintains the desired test temperatures in the specimen. The water temperature within the specimen can be maintained within a few degrees of the hot water bath temperature with only a nominal amount of circulation on each pressure cycle. If an ambient temperature condition is desired it is possible to replace the hot water bath and circulating pump with a city water (45 psi) line. The maximum pressure in the water manifold is observed by reading a pressure gage in that line, and the pressure relief valve in the oil portion of that leg is used to control that maximum pressure.

The pressure cycle obtained from this equipment is shown in Figure 8.12. As one can expect, the solenoid should operate with equal on and off times, because when one leg is on the other leg is off. Since a constant volume output pump is used, the pressure built-up rate is almost linear and dependent on the size of the pump, the number of specimens being tested, and the amount of water flowing through the needle valve. The maximum pressure is a horizontal line on the pressure time chart, and it is controlled by the pressure relief valve.

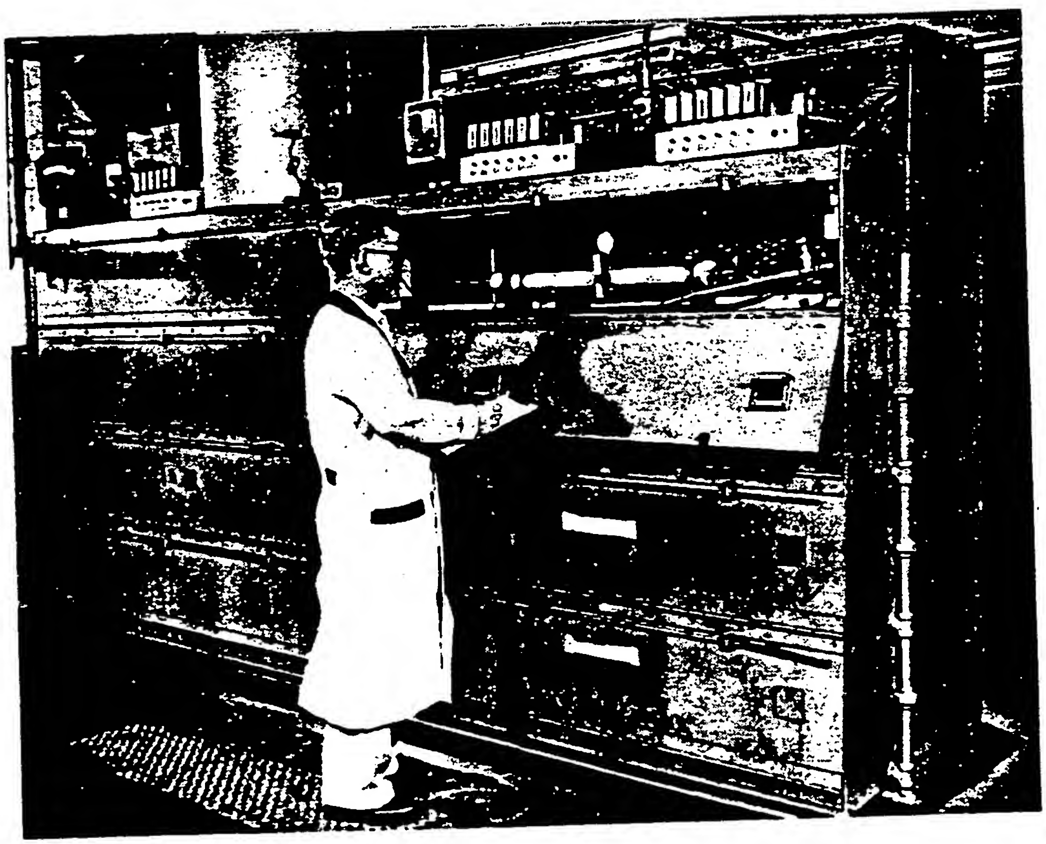


Figure 8.11 Cyclic internal pressure pipe test equipment. (Courtesy of A. O. Smith Corp.)

When the solenoid clicks to the off portion of the cycle the test pressure has a very rapid drop off to the minimum level controlled by the circulating pump. This rapid drop-off is desirable from the viewpoint of the time required to recharge the accumulator with this low pressure.

When using this equipment the operator will first adjust the pressure relief valves to the desired amount with no specimens attached. Then, with the oil pump turned off he will connect the specimens, open the needle valve and turn on the circulating pump to obtain temperature stability of the water within the system. It is necessary to bleed all the air from the specimens to obtain fast cycling performance. After the temperature has stabilized he will close the needle valve to the desired amount and start the oil pump and electric cycler. The electric cycler is adjusted to equal on and off times, so the maximum pressure is applied for just an instant during each pressure cycle. These adjustments of the needle valve, cyclic rate, and pressure relief

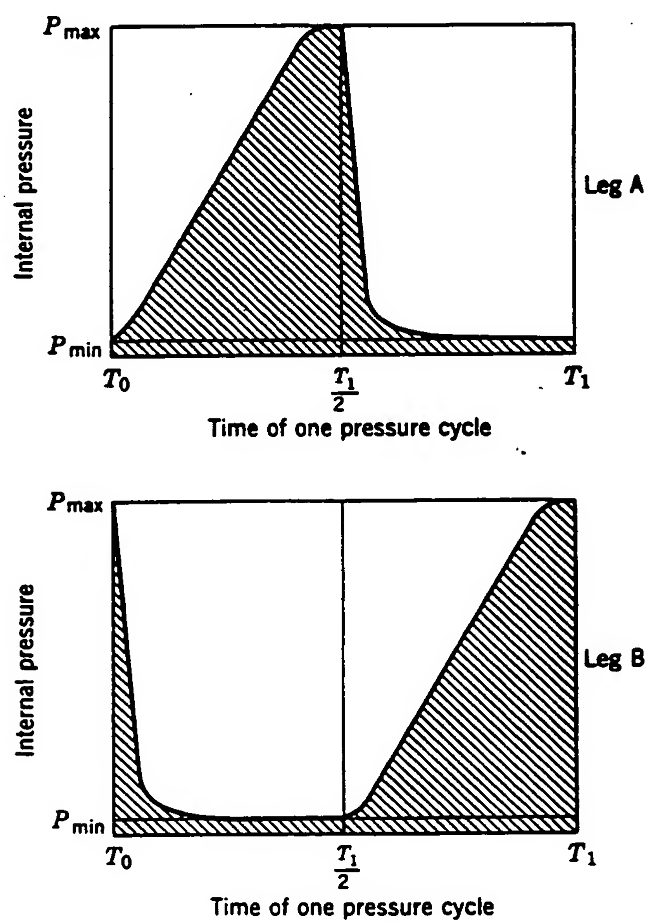


Figure 8.12 Graph of one pressure pipe cycle. (Courtesy of A. O. Smith Corp.)

valves have been found to remain constant for extremely long periods of time and rarely require additional adjustment during a test. The coupling of the failure-detection apparatus will be discussed later.

All the components of this equipment are commercially available, and during the development of this equipment several components required frequent replacement. The solenoid operated four-way oil valve required the most maintenance. This problem has been completely resolved by using a valve with an oil-immersed solenoid. Many pressure relief valves have been found satisfactory, but these must be of the direct spring operating type, for unsatisfactory performance has been found with the pilot operated designs. An electric cycler which has an adjustable rate of 3 has been found desirable. The only major problem remaining is with the accumulator. The membrane type gives excellent performance but relatively short life. The piston-type accumulators give long life but do not offer a complete fluid separation, for a small quantity of oil is transferred to the salt water. This presents no problem for the short-term test, but since the oil will build up over a period of months, the system must be cleaned.

Exactly what constitutes failure is dependent on the end use of the pipe. If the pipe is to carry large quantities of a disposable fluid it could exhibit a small leak without being classed as failed, whereas if this fluid were extremely costly or dangerous very small losses would be serious. Failure is defined in relation to the fluid containing characteristics of the pipe, and one of the reasons salt water is used is to facilitate its detection. Failure has been defined when used with this equipment as the passage of salt water through the wall of the specimen so the resistance is lowered to a level of between 10 and 20 megohms. A very small amount of salt water passing through a pin-hole leak or fine crack is sufficient to classify the specimen as having failed. In many cases, the pressurizing capacity of the pipe is unaffected by these small failures. One terminal of the detector is grounded to the steel pipes of the salt water manifold and the other terminal of each channel is connected to a 300-mesh brass screen wrapped around the OD of the test specimens. The screen covers the center portion of the specimen only and does not cover the end portion which, because of the end closure, may have some additional bending stresses. This detection method picks up weeping failures and wall ruptures with equal ease. The 10 to 20 megohm resistance required to classify failure was selected as being extremely sensitive to small failures but unaffected by humidity conditions. Small cracks and weeping failures have been determined as being of a progressive

nature. The use of this failure criteria and detector establishes failure at a very early state. It is a very constant and reproducible criteria. A simple check-out procedure with necessary instrumentation is periodically used to ascertain the consistency of the failure detector.

A counter, operated by the equipment's electric cycler and coupled through the respective channel relay, is used for each specimen being tested. When failure is measured, the counter is automatically stopped, and this permits continual round-the-clock operation of the equipment with reproducible failure detection. When weeping failure occurs, the loss of fluid is so negligible that other specimens on the manifold continue to experience the same pressure cycle and the test continues. When a rupture failure occurs, the salt water is splashed over adjacent specimens and the entire test is stopped until the operator returns.

Although this equipment has been used extensively for testing thin-wall reinforced plastic pipe, it is not limited to testing pipe of that description. It has been used on a limited number of tests of thick-walled glass reinforced plastic pipe and also on unreinforced thermoplastic pipe. Ruptures occurred on some of the thermoplastic pipe, and the thick-wall thermosetting pipe failed by methods similar to the thin-wall thermosetting pipe.

The following experiments were run on this equipment either to evaluate the variables in the test or to rate the quality of a pipe. The first experiment covers an investigation of the effect different cyclic rates (cpm) have on pipe life. The prime interest here was to gain information that would allow the test to be run as rapidly as possible, and as an upper limit a rate of 33 cycles per minute was used. This

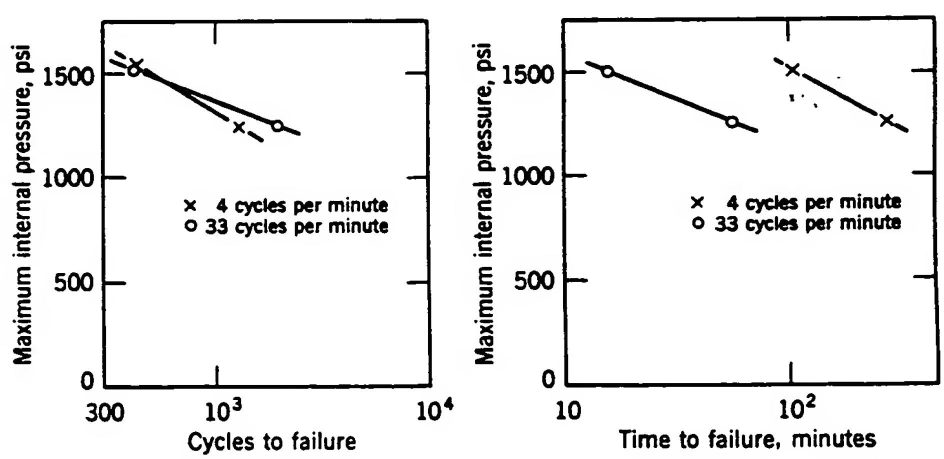


Figure 8.13 Cyclic rate effects on pipe life (2-inch-diameter pipe). (Courtesy of A. O. Smith Corp.)

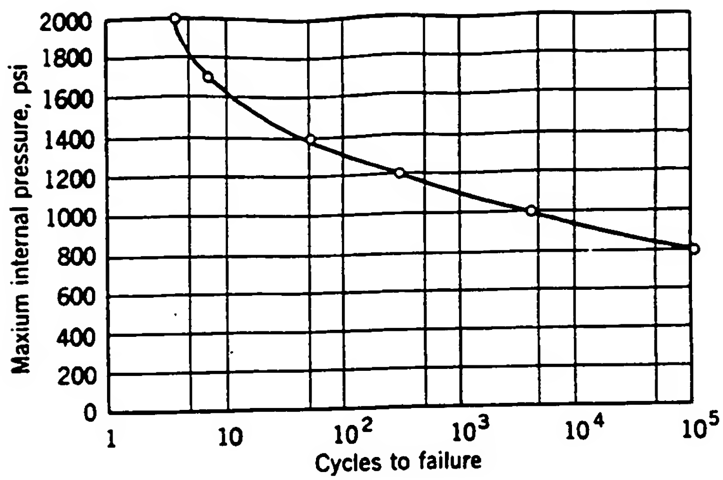


Figure 8.14 Short-time cyclic pressure life. (Courtesy of A. O. Smith Corp.)

was the most rapid rate at which the equipment would operate. A rate of 4 cycles per minute was selected for the lower rate. The test was at room temperature of 2-inch thin-wall glass reinforced epoxy pipe, and all failures were of the weeping type. Two maximum pressures (1,250 psi and 1,500 psi) were used and three specimens were tested at each pressure-rate combination. The graph in Figure 8.13 shows a plot of the average results for each combination. The spread of results was such that no difference was detectable in cycles-to-failure measurements between the two cyclic rates at each of the two pressure levels. The lower pressure, of course, lasted significantly longer. The absolute time duration of the tests was, therefore, an inverse ratio of the cyclic rates. From this limited information, the fastest cyclic rate possible was selected for additional tests. Future plans include an enlarged investigation to evaluate the rate of pressure build-up as well as the cyclic rate and also to relate cyclic-pressure performance to steady-pressure performance.

The second experiment deals with the question "How is pipe life affected by different maximum pressures?" Again a sample of 2-inch thin-wall pipe was used, and all failures were of the weeping type. Six specimens were tested at room temperature at maximum pressures ranging from 2,000 psi to 800 psi. Failure times are indicated as circles in Figure 8.14. Burst on this pipe is estimated at between 3,500 psi and 4,000 psi, with one cycle weeping estimated at approximately 3,000 psi. From a large quantity of other data a linear relationship was expected over the lower pressure range when the cycles to failure are plotted on a log scale. This data was also plotted on log-log paper and did not produce a linear relationship over the entire range. The results clearly show a rapid drop-off in cycles to

failure over the higher pressure range and a leveling out to the linear relationship over the lower pressure range. In applying these results to predicting lower pressure life, the slope over the lower pressure range should be considered. A policy has been adopted to discard the results at the higher pressures which give failure counts in less than 1,000 cycles, similar to discarding burst data, and to make least-squares regression calculations on data over the lower-pressure range for determining a pipe's character in this test. In making the regression calculations, cycles to failure is considered a logarithmic function and maximum internal pressure a linear function. A calculated correlation coefficient tells how accurately the data fits this linear regression. A correlation coefficient of less than about 0.85 is considered a poor fit. Extrapolated performance can be estimated accurately only by use of these statistical procedures. Similar statistical procedures have been used to rate the physical properties of different materials.

One of the variables investigated quite thoroughly is the effect of the finish on the glass fibers used in pipe fabrication. A classical approach has been taken, varying only the glass finish and keeping all other factors (materials and fabrication techniques) constant. It can be debated that possibly some item should have been altered to improve results obtained from the "poor" finish, and this area was covered by other experiments with no success. The purpose of this experiment was to classify the performance of good and poor pipe over a wide range of maximum pressures. Room-temperature tests were used, and specimens made with glass having the two finishes were placed on test at maximum internal pressures varying from 200 psi up to 1,200 psi at 200-psi increments. Eight specimens were used for each group, and the doubling-up of specimens was done at the higher pressure levels. The lines drawn on Figure 8.15 show the least-squares regression of the two samples. All specimens made with glass having finish B failed in less than ten million cycles, or one year. The specimen made with glass having finish A and tested at 200 psi has not failed after more than fifty million pressure cycles, and since the 400 psi specimen is the lowest pressure at which failure has occurred from that sample, the line is shown dotted below 400 psi. It is interesting to note the correlation coefficients for these two regression lines. Glass with finish A not only produced the better-quality pipe but was also very reproducible, with an extremely high correlation coefficient of 0.996. Glass with finish A had a low correlation coefficient of 0.996. Glass with finish B had a low correlation coefficient of 0.77. The statistical calculations of these lines clearly show a significant difference. Glass with finish A gave the significantly superior pipe.

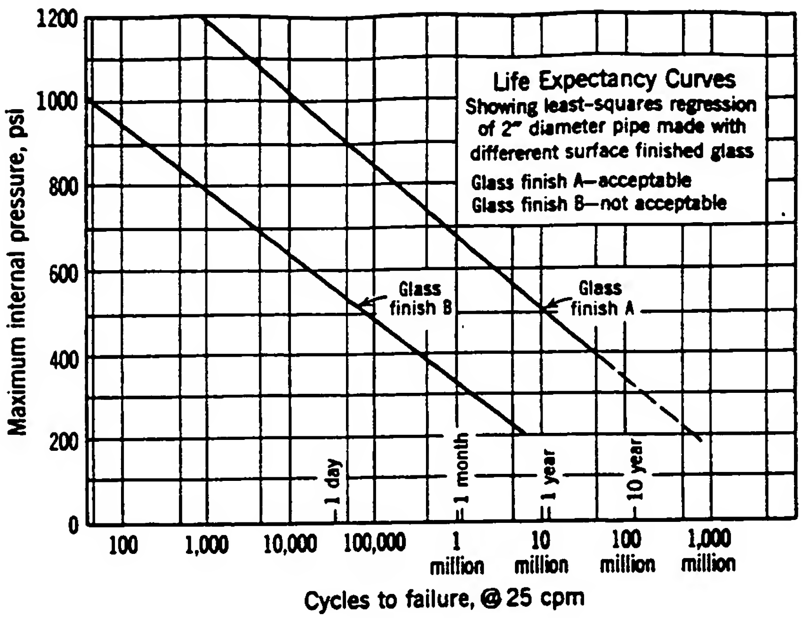


Figure 8.15 Life expectancy curves of pipe. (Courtesy of A. O. Smith Corp.)

CRITICAL COLLAPSE TEST OF THIN-WALL CYLINDERS

A criterion for predicting the critical collapse pressures of thin-walled fiber reinforced cylinders as described in this section has been developed by F. R. Pflederer of A. O. Smith Corporation (10). The equation used is a modification of the type used for cylinders made from homogeneous and isotropic materials. This modification is directly related to the elastic properties of the resin and reinforcing materials. The theoretical data will be compared with actual pressure tests on various cylinders.

The critical collapse, or buckling pressure of a cylinder, is produced solely by the cylinder dimensions and material elastic properties and is independent on the strength of material from which the cylinder is made. Buckling or elastic stability can be viewed as a property of the material similar to Poisson's ratio being a property of the material. Since buckling of a cylinder subjected to external pressure occurs by the cylinder's circular cross section becoming elliptical, it is obvious that the stiffness in the circumferential direction contributes most significantly to this failure. It would also be intuitive to expect the stiffness in the axial direction to have little or no effect on this critical collapse pressure.

Investigation into the critical collapse pressure of reinforced plastic cylinders was facilitated by several years of work, directed toward

developing elastic constants of a reinforced plastic layer based on the elastic constants of the resin and reinforcement, reinforcement angle, and content. The development of these composite orthotropic elastic constants for a layer was possible because, fortunately, the components, resin and glass, are essentially homogeneous and isotropic in nature and do obey conventional rules which are understood for homogeneous and isotropic materials. Extensive work has been conducted to develop these elastic constants (11).

One of the simplifying assumptions reported was that the resin obeys Hooke's law of linearity in its stress-strain relations. It was well known that this was not true. Since a linear modulus of elasticity could be used to closely approximate this initial portion of the true resin stress-strain curve, however, it was expected that predictions of elastic constants at low stress levels would be relatively accurate. Since buckling of thin-wall cylinders occurs at relatively low compressive stress levels, it was expected that the elastic constants developed would be satisfactory for predictions of the critical collapse.

The accepted formula for predicting critical collapse of thin-wall cylinders composed of homogeneous material having isotropic properties is as follows (12):

$$P_{\mathrm{CR}} = \frac{1}{4}\frac{E}{(1-\mu^2)}\frac{(t)^3}{(r)^3}$$

where P_{CR} = critical collapse pressure, psi
E = modulus of elasticity
μ = Poisson's ratio
t = wall thickness
r = radius of pipe

Based on advice from Professor G. Pickett of the University of Wisconsin a $g_{11}G^1$ value describing the hoop stiffness of a reinforced plastic cylinder was substituted for the elastic values of the preceding equation. This action was thought appropriate, although it was primarily intuitive in nature. The value describes the stiffness of a filament-wound cylinder in the hoop direction. This transfer created the following equation, which relates the critical collapse pressure to the component resin and glass properties:

$$P_{\mathrm{CR}} = \tfrac{1}{4}(g_{11}G^1)\frac{(t)^3}{r}$$

The latter equation has been used to make predictions of critical collapse pressures of thin-wall directionally reinforced cylinders as shown in Figures 8.16 and 8.17. The angle of reinforcement referred

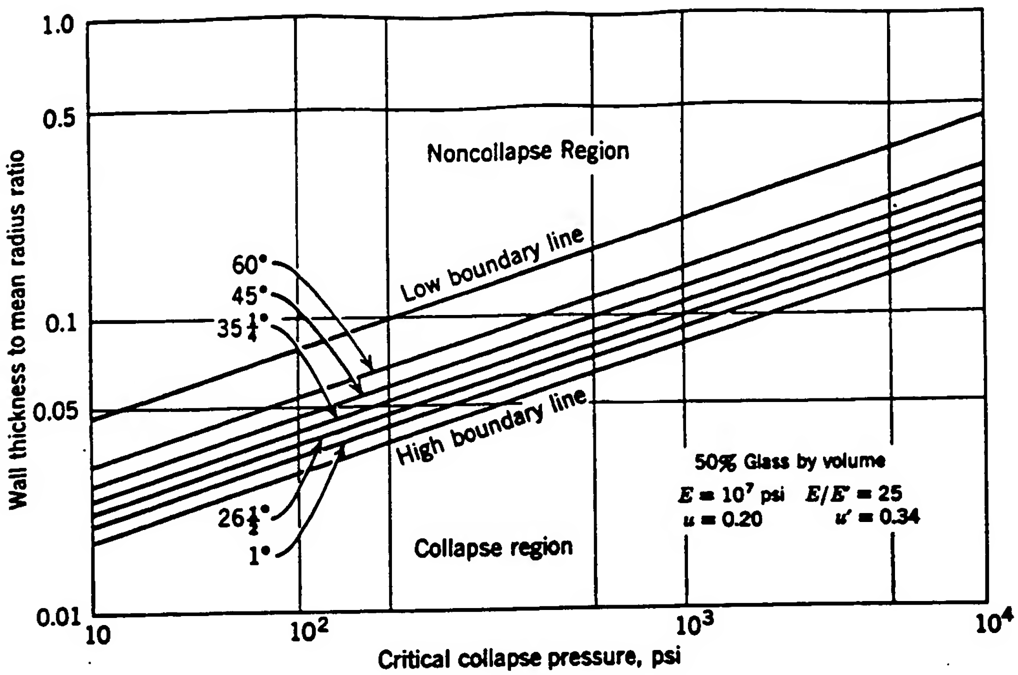


Figure 8.16 Predicted cylinder critical collapse pressure versus fiber orientation. (Courtesy of A. O. Smith Corp.)

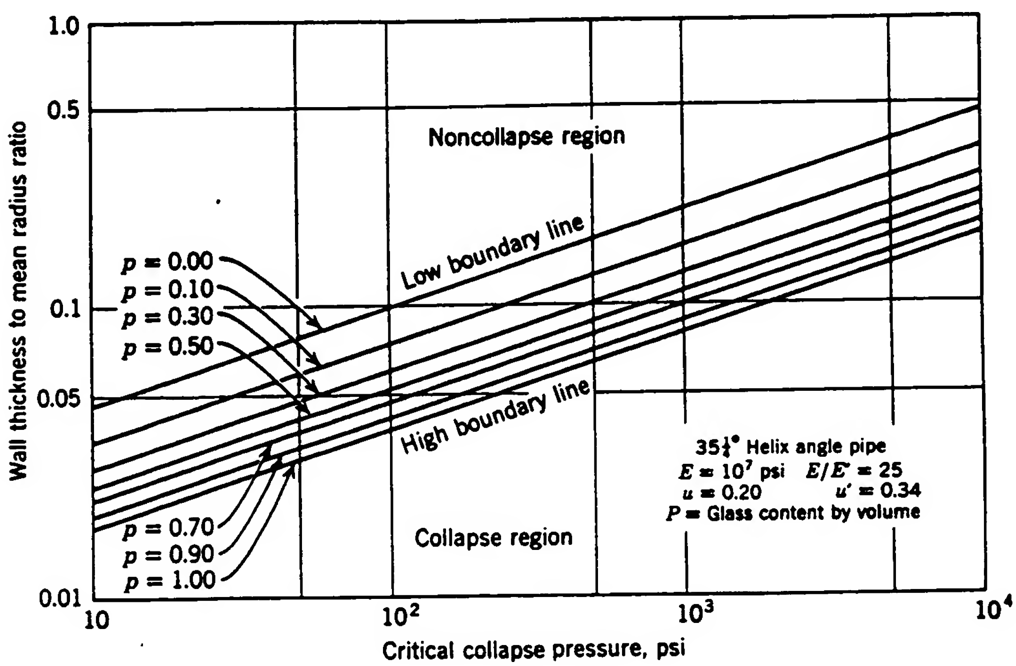


Figure 8.17 Predicted cylinder critical collapse pressure versus glass content. (Courtesy of A. O. Smith Corp.)

to the helix angle at which the fibers were placed on the cylinder as one would view the helix angle of a common screw thread. The reinforcement would, of course, be balanced with the number of fibers in a right-hand helix equaling the number of fibers in the left-hand helix.

The predicted collapse pressures shown in these two graphs are based on the cylinder being fabricated from fibers having a Young's modulus of 10^7 psi and a Poisson's ratio of .20 with a resin having a Young's modulus of 0.4×10^6 psi and a Poisson's ratio of 0.34, which would be true using Dow Chemical's DER 331 resin cured with MDA. Figure 8.16 shows how predicted critical collapse pressures were influenced by different reinforcement orientations, and Figure 8.17 shows how, with any particular angle of reinforcement, the predicted critical collapse pressure was influenced by glass content. These figures can be used directly for design purposes. However, Figure 8.18 has been added to facilitate design for critical collapse of a cylinder with any combination of reinforcement angles. The $g_{11}G^1$ values in Figure 8.18 can be used directly in the equation. These stiffness values can be used for cylinders fabricated using several angles of reinforcement when they are properly weighed.

For example, suppose a designer wanted to determine the critical collapse pressure of a cylinder having a t/r ratio of 0.05, a glass content of 0.5 using resin and glass with the mentioned elastic properties, and reinforced with fibers orientated 2-circumferential to 1-longitudinal. The $g_{11}G^1$ values taken from Figure 8.18 would be 5.2×10^6 psi and 1.2×10^6 psi for the hoop and longitudinal directions respectively. An average value of 3.9×10^6 psi would be determined when the stiffness values were weighed in the same proportion as the reinforcement. This value of 3.9×10^6 psi used in the equation would predict the cylinder to fail at 122 psi external pressure.

Any calculated predictions are accurate only for conditions upon which the mathematics are derived which follows the conditions:

1. The cylinder is thin-walled, maximum t/r of about 0.15.
2. The cylinder is relatively uniform in wall thickness.
3. The glass content is relatively uniform and of a known value.
4. The cylinder cross section under study is unaffected by end closures or enlarged sections (usually a minimum of 9 diameters long).

Experimental values of critical collapse pressure were determined on pipe subjected to external pressure. The procedure used was to build up pressure on the outside of the cylinder while the inside of the

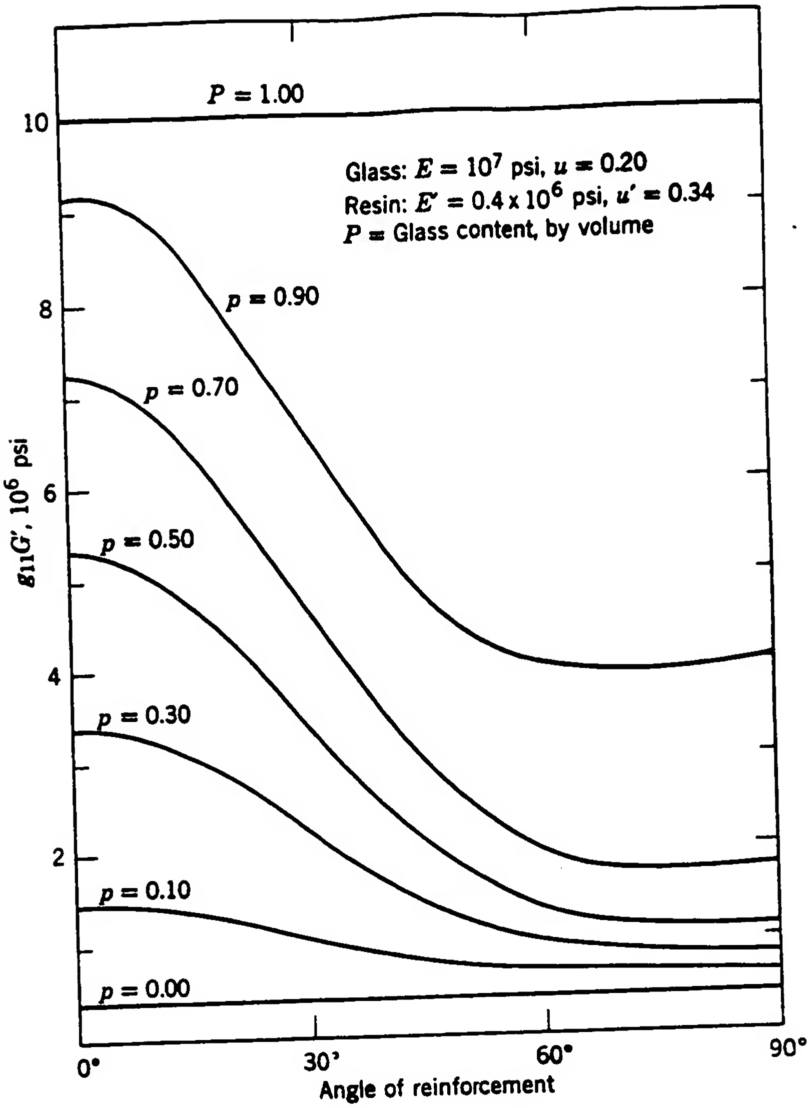


Figure 8.18 Computed stiffness chart. (Courtesy of A. O. Smith Corp.)

cylinder was vented to the atmosphere. To accomplish this, the filament-wound cylinder was capped and placed inside a larger steel container and the volume between the two filled with water.

The test procedure followed was to cap the steel container and then add water at a constant rate and record the pressure rise. The pressure rise was in direct relation to the volume of water added up to the point of critical pressure. At that point, the filament-wound cylinder deformed from its circular cross section with an accompanying reduction in its internal volume. This reduction in its internal volume was reflected as a reduced rate of pressure increase. This is shown graphi-

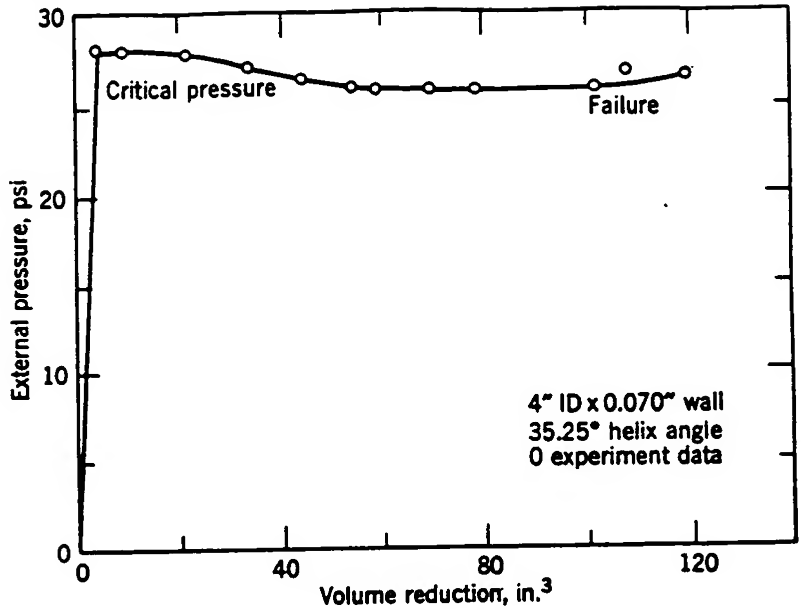
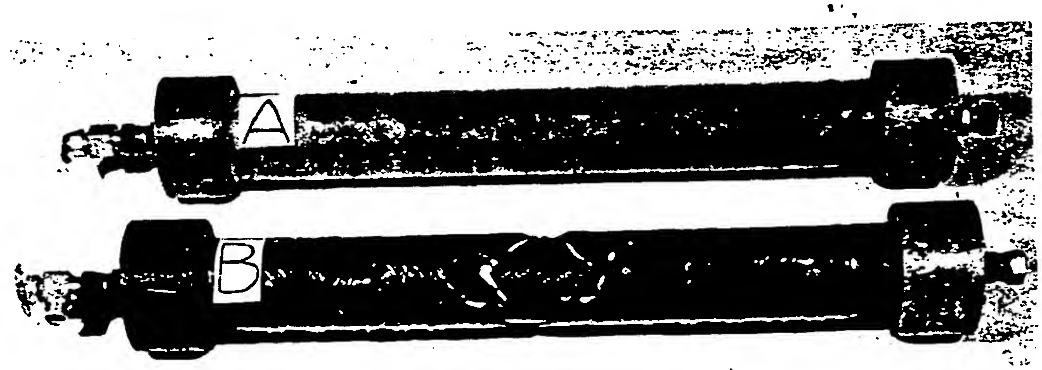


Figure 8.19 Determination of actual critical pressure test. (Courtesy of A. O. Smith Corp.)

cally in Figure 8.19. The important part of this figure was the highest pressure on the linear portion of the graph. Other portions of the graph were affected by unrelated experimental procedures.

The volume units were related to the length of the specimen, and the decrease in pressure after the critical point had been reached was affected by air inside the steel chamber. The pressure at the instant of catastrophic failure was either higher or lower than the critical pressure depending on the specimen geometry. When catastrophic failure did take place, it appeared as shown in Figure 8.20. The specimens shown in Figure 8.20 were tested with a free end condition



Figur 8.20 Typical collapse pressure. (Courtesy of A. O. Smith Corp.)

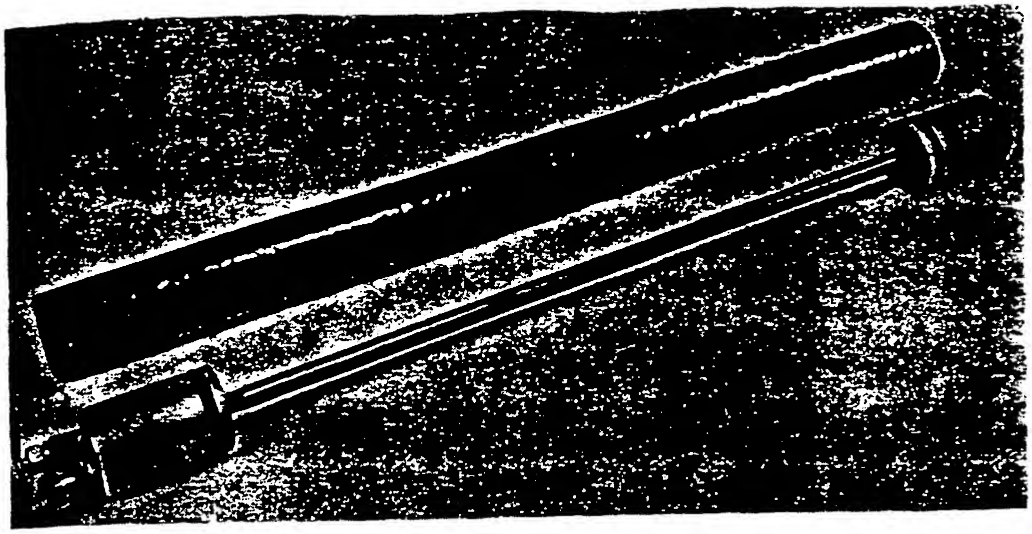


Figure 8.21 Test fixture to eliminate axial load. (Courtesy of A. O. Smith Corp.)

in which the axial compressive load was applied to the specimen. Experimental measurements were also made on specimens equipped with fixturing, as shown in Figure 8.21, which eliminated the axial load. The critical pressure determined by these two methods differed by about 5 per cent, which was within the experimental variation.

The measurement of critical collapse also included an investigation into the time-dependent features of this type of failure in a thin-wall cylinder. Using the mentioned procedure for determining critical collapse, it was possible to stop the water addition at any point on the graph shown in Figure 8.19. It was noted that if the critical pressure had been reached and that pressure was maintained, catastrophic failure took place within a few hours, depending on how far past the critical point the test had gone. This would take place even though the pressure was below the critical when the elliptical deformation had already begun. However, when the pressure was held at a point before the critical pressure had been reached, there was no failure after several weeks of steady pressure at 250,000 pressure cycles.

This lack of time dependency of buckling failure can be explained because the pressures involved in testing this thin-wall cylinder were quite low and created only very low compressive stresses. All tests conducted which showed no time dependency of failures below the critical pressure were made on cylinders having a thickness-to-radius ratio of 0.07 or less. Time dependency would be expected for tests of thick-wall cylinders where the compressive stress level would be high enough to create creep and plastic flow of material.

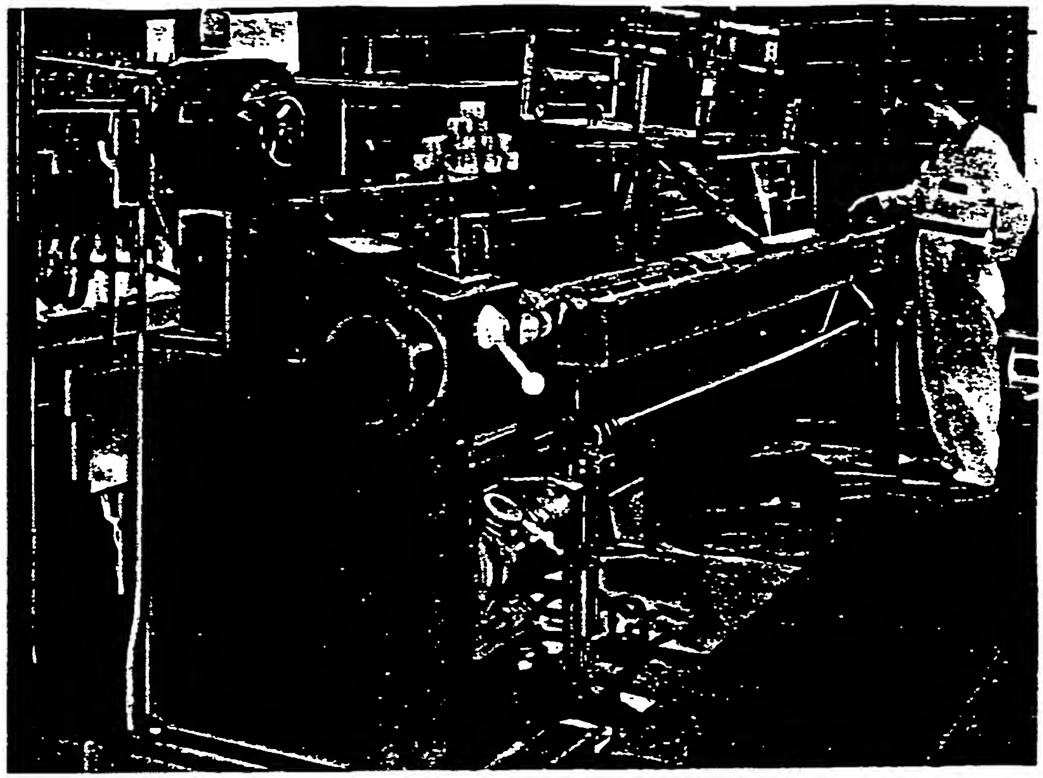


Figure 8.22 Experimental winding machine. (Courtesy of A. O. Smith C rp.)

A study was conducted to determine the merit of the predicted collapse values by correlating them with actual measured collapse values. To make the correlation most meaningful it was thought desirable to alter some variable over a wide range. Theoretically, this could have been the elastic properties of the resin or glass, the reinforcement content and angle, or the cylinder dimensions. Considering both the academic and experimental aspects, the reinforcement angle was selected as the item to be varied.

Two-inch-diameter cylinders by approximately $\frac{1}{16}$-inch wall were fabricated using helix angles of wind of 2°, 15°, 35¼°, and 60°. These were made by a wet-winding procedure on the equipment shown in Figure 8.22. The resin and glass used was the same for all specimens and had the elastic constants shown in Figures 8.16, 8.17, and 8.18.

All specimens in this correlation study were tested using the fixture, shown in Figure 8.21, which eliminated the axial load from the specimen. The critical pressure was measured on the specimens before the calculation of the predicted values. Although this eliminated the possibility of test operator bias, it was in reality done that way be-

Tabl 8.1 Actual and Theoretical Critical C llapse Pressures of Cylind rs with Varying Glass Content and Orientati n (10)

Helix Angle	Wall	Glass Per Cent	Critical Pressure Tested	Critical Pressure Calculated	Per Cent Difference
2	.045	53.48	108.5	120.5	+10.0
2	.045	53.48	117.0	120.5	+2.9
2	.042	55.6	102.5	102.0	−0.5
2	.042	55.6	102.5	102.0	−0.5
15	.047	55.84	125.5	128.0	+2.0
15	.047	55.84	125.0	128.0	+2.3
15	.050	48.98	135.0	135.4	+0.3
15	.050	48.98	137.0	135.4	−1.2
15	.049	46.68	137.0	122.0	−12.3
15	.049	46.68	127.5	122.0	−4.5
$35\frac{1}{4}$	.050	50.71	91.0	87.2	−4.4
$35\frac{1}{4}$	.058	49.09	126.0	128.3	+1.8
$35\frac{1}{4}$	.067	45.18	187.0	181.8	−2.9
$35\frac{1}{4}$	.069	46.22	186.0	197.9	+6.1
60	.055	50.86	55.0	53.6	−2.6
60	.055	50.86	55.0	53.6	−2.6
60	.068	40.18	84.5	81.2	−4.1
60	.068	40.18	86.0	81.2	−5.9
60	.067	40.94	75.0	88.4	+15.1
60	.067	40.94	92.0	88.4	−4.1

$$\text{Per Cent Difference} = \frac{\text{Critical pressure calculated—Critical pressure tested}}{\text{Critical pressure calculated}} \times 100$$

Mean = .255%
Standard Deviation = 5.93%

cause the glass contents used in calculating the predictions were determined from burnout tests conducted on the failed specimens. Table 8.1 shows results, along with the predicted collapse pressures and variation of the predictions from the experimental values. This per cent variation was assumed to be of a normal distribution, and confidence limits then applied to the predicted values.

SOAK-CYCLE TEST (13)

The field failures which defied explanation by conventional testing methods gave rise to a thorough review of life testing techniques for

fiber glass pressure vessels. A new accelerated life test was developed which yields more reliable results than conventional tests.

Accelerated life testing is always a large problem because it is difficult to design a test that can be translated into a realistic minimum service life or which can even simulate the mode of failure in actual service. In the case of spherical fiber glass pressure bottles, life testing in the past has consisted chiefly of pressure cycling from zero to service pressure at a rate of 2 to 7 cycles per minute.

The earliest cycle requirements were 10,000 cycles at room temperature, plus 2,000 cycles at 200°F, followed by a minimum burst of ⅝ the service pressure. Present requirements are much more strict: 11,000 cycles at room temperature; 5,000 cycles at 200°F; 1,000 cycles at minus 65°F; 3,000 cycles at 120°F; and 95 per cent relative humidity. Although this type of fatigue testing is useful for ranking purposes, it does not in any way simulate the actual service for which the vessel will be employed. Furthermore, these tests do not take into account the effects in relation to pressure, temperature, and humidity.

When field failures began to be reported which could not adequately be explained in terms of cycles to failure, even under extreme humidity conditions, a new type of test was instituted, which attempted to simulate actual field usage under severe temperature and humidity conditions. This test, which may be termed a "soak-cycle" test, consists of maintaining a vessel which is hydrostatically charged to service pressure in a severe temperature-humidity environment and cycling it from service pressure, to zero, to service pressure three times daily. This regime is continued until failure occurs, and the number of hours to failure is the test result.

Tests of this type have been performed at 160°F and 95 per cent relative humidity at rated service pressure (45 per cent of minimum burst pressure), and at 120°F and 95 per cent relative humidity at 60 per cent of the minimum burst pressure. The results of these tests have shown that this soak-cycle technique is considerably more sensitive in differentiating the long-term humidity resistance of pressure vessels fabricated with various materials than the old testing method of "fast cycling" in a temperature-humidity environment. Whereas conventional testing showed an improvement factor of approximately 4.2 for uncoated spheres fabricated with silane-sized glass, the soak-cycle tests shows an improvement factor of 7.5. Since the soak-cycle test more closely resembles actual usage, its results are more realistic as an aid in setting service life limits. Test results are tabulated in Table 8.2.

Table 8.2 *R sults of Humidity Tests n Glass Roving W und Spheres (13)*

Glass Finish	Test Conditions [1]		Average Test R sults	
	Temp rature, °F	Pressur , psi	Soak Cycle, hours [2]	Conventional Cycle, cycles [3]
Oil and starch, uncoated	160	3,000	158	1,000
Silane, uncoated	160	3,000	1,180	4,200
Silane, uncoated	160	3,000	—	13,275
Silane, uncoated	160	4,000	600	—
Oil and starch, uncoated	120	4,000	32	—
Silane, coated	120	4,000	1,324	—

[1] Relative humidity 95 per cent.
[2] Maintain vessel under pressure until failure, cycles from zero to pressure at 3 times daily.
[3] Cycles from zero to pressure at 2 to 5 per minute to failure.

Further tests were conducted to determine whether this testing technique could quantitatively bring out the effects of aging better than standard testing techniques. Spheres belonging to three different categories were tested in soak-cycle tests and in conventional tests, such as room-temperature burst tests, room-temperature cycle tests, and fast-cycle humidity tests. The categories were: vessels stored for three years, but never used; vessels returned after 200 or more flight hours and three or more years old; and newly fabricated vessels, using the same materials.

Table 8.3 shows the results of the soak-cycle test. It can be seen that the soak-cycle test was able to differentiate the three categories by several orders of magnitude. The used spheres appeared to have only 5.7 per cent of their original life left.

Table 8.3 *Results of Soak-Cycle Tests on Aged and New Spheres (13)*

Condition	Hours to Failure	Per Cent Original Life
Stored 36 months, not used	21	13.3
Stored 40 months, used 500 hours	9	5.7
New spheres, not used	158	100

Test c nditi ns: 300 psi, 160°F, and 95 per c nt r lative humidity.

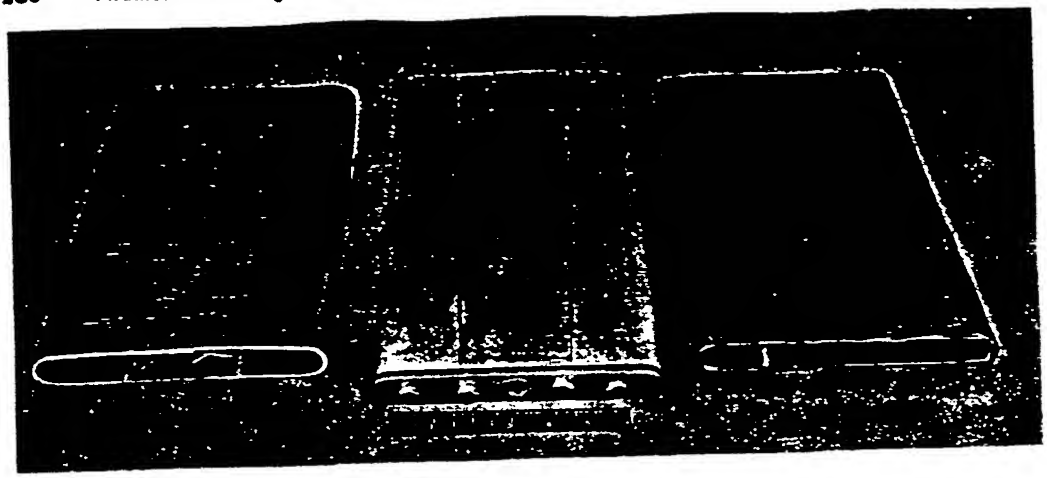


Figure 8.23 Flat unidirectional flexure and tensile specimens are cut from flat-wound sections; three-part aluminum mandrel is shown in center. (Courtesy of NAA Rocketdyne.)

RESIN TESTS

Some of the standard ASTM test methods as well as new tests have been developed principally to evaluate and/or control resin performance. Tensile, compressive, and shear tests are conducted on unfilled and glass-filament-filled resins to obtain strength, elongation, and flexibility properties. Other tests are performed to categorize wetability on filaments, produce uniform B-stage system, and standardize cure.

Many of the unfilled tests cannot be directly correlated in setting up standard controls for general reinforced plastics. These tests are used predominantly for specific end-item control or to set up quality control during manufacture.

The Society of Plastics Engineers, Inc., plastics properties professional activity group, has set up a recommended list of materials' properties to be considered for use by suppliers and users (14). The standards in Table 8.4 can be used in material selection.

Resin Fiber

Various test methods are being used to develop resin-fiber strength. The specimens employed have taken the shapes of rods, plates, rings, and tubes. The Boeing-Narmco tensile test specimen (6) is reported to produce the highest tensile strength value for single-end glass strands impregnated with epoxy resin. Values of 479,000 psi are reported with glass fiber ECG 150 1/0 890 finish.

Other techniques involving casting small beams of resin reinforced

with glass strands are used. The resin is concentrated near one end only. Loading of the fiber induces shear between the strands and the resin. A comparison of the calculated stiffness of this type of beam and its value in bending yields a measure of shear rigidity of the bond between the strand and the resin.

Resin Shrinkage

Studies of glass filament–resin shrinkage stresses have been conducted (15, 16). The use of small-diameter fibers in thin stress-free resin castings results in detecting photoelastic stresses which are due only to the resin-glass interaction. Stress difficulties produced by resin exothermic heat and mold constraint are circumvented.

Specimens are prepared in a vacuum desiccator. Catalyzed liquid resin is poured in small amounts on the surface of mercury which is in the desiccator. A glass fiber is placed on top of the resin puddle, followed with more resin carefully added to ensure wetting of the fiber. The desiccator is closed. Vacuum and nitrogen gas is alternately applied for several cycles, ending with nitrogen at a pressure slightly reduced from atmospheric to allow for expansion of the gas at the cure temperature. The inert nitrogen is used because of the inhibiting effect of air on resin cures. Cure of resin is accomplished by placing the desiccator in an air oven.

When specimens without fibers are produced by this method they show no birefringence when viewed between cross polaroids. With glass-resin specimens definite stress patterns are viewed. These thin specimens are analyzed by means of a compensator Senarmont technique (17). It is reported that this photoelastic technique when used with Rohm and Haas polyester "Paraplex P-43" resin with single E-glass filament resulted in the following analysis (15):

1. The axial stresses were much greater than the radial stresses.
2. The axial stress maxima depend on fiber length until a certain minimum length is exceeded.
3. The condition of the fiber surface influences the axial stress achieved.
4. The stresses arise from differential contraction effects between glass and resin.

With multiple parallel filaments the results show:

1. The axial stresses diminish rapidly as the spacing decreases.
2. The degree of resin stresses, tensile or compressive, depends on fiber spacing.

Table 8.4 Society of Plastics Engineers Standard Property List for Plastics Materials (14)

Property	ASTM Method (see Note 1)	Test Specimen Unless Specified Otherwise by Appropriate ASTM Material Specification: Molding Method	Nominal Size (inches) (see Note 2)	Conditioning (see Note 1)	Unit	$\bar{x}$ *	σ †
Apparent Density (free-flowing)	D-1182	—	—	—	g/cu cm		
Apparent Density (nonpouring)	D-954	—	—	—	g/cu cm		
Bulk Factor	D-1182	—	—	—	—		
Specific Gravity	D-792 Method A	—	—	D-618	—		
Mold Shrinkage	D-955	Compression or transfer (see Note 3)	$\frac{1}{2} \times \frac{1}{2} \times 5$	D-618	in/in		
Thermosets	D-955	Injection, parallel	$\frac{1}{2} \times \frac{1}{8} \times 5$	D-618	in/in		
Thermoplastics	D-955	Injection, diametric	$\frac{1}{8} \times 4$ disc.	D-618	in/in		
Flow Rate	D-1238	Acc. to Material Specification	—	Acc. to Material Specification	g/10 min		
Dielectric Constant	D-150	Compression (see Note 3)	$\frac{1}{8}$ thick	D-618 Procedure B	—		
60 cycles/sec							
10^3 cycles/sec							
10^6 cycles/sec							
P wer Fact r	D-150	Compression (see Note 3)	$\frac{1}{8}$ thick	D-618 Procedure B	—		
60 cycles/sec							

10^3 cycles/sec					
10^6 cycles/sec					
Volume Resistivity	D-257	Compression	$\frac{1}{8}$ thick	D-618 Procedure B	ohm-cm
		(See Note 3)			
15 seconds					
2 minutes					
20 minutes					
Arc Resistance	D-495 Stainless Steel Electrode System	Compression (see Note 3)	$\frac{1}{8}$ thick	D-618 Procedure B	sec
Dielectric Strength	D-149 15 (a & b)	Compression (see Note 3)	$\frac{1}{8}$ thick	D-618 Procedure B	volts/mil
Tensile Strength	D-638	Compression	Type 1 $\frac{1}{8}$ thick	D-618 Procedure A	psi
Thermosets	Speed A	(See Note 3)			
Thermoplastics	Speed B (See Note 4)				
Tensile Elongation	D-638	Compression	Type 1 $\frac{1}{8}$ thick	D-618 Procedure A	per cent
Thermosets	Speed A	(See Note 3)			
Thermoplastics	Speed B (See Note 4)				
Elastic Modulus	D-638	Compression	Type 1 $\frac{1}{8}$ thick	D-618 Procedure A	psi
Thermosets	Speed A	(See Note 3)			
Thermoplastics	Speed B (See Note 4)				
Flexural Strength	D-790	Compression		D-618 Procedure A	psi

Tabl 8.4 Continued

Property	ASTM Method (see Note 1)	Test Specimen Unless Specified Otherwise by Appropriate ASTM Material Specification: Molding Method	Nominal Size (inches) (see Note 2)	Conditioning (see Note 1)	Unit	$\bar{x}$ *	σ †
Thermosets		(See Note 3)	5 (c)				
Thermoplastics			5 (a) (1) $\frac{1}{8}$ thick				
Flexural Modulus	D-790	Compression		D-618 Procedure A	psi		
Thermosets		(See Note 3)	5 (c)				
Thermoplastics			5 (a) (1) $\frac{1}{8}$ thick				
Compressive Strength	D-695 Speed 8 (b)	Compression (see Note 3)	$\frac{1}{2} \times \frac{1}{2} \times 1$	D-618 Procedure A	psi		
Compressive Modulus	D-695 Speed 8 (b)	Compression (see Note 3)	$\frac{1}{2} \times \frac{1}{2} \times 1$	D-618 Procedure A	psi		
Hardness (Rockwell)	D-785 Method A	Compression (see Note 3)	$\frac{1}{4}$ thick	D-618 Procedure A	State scale used		
Impact Resistance	D-256 Method A	Compression (see Note 3) Milled notch as per Sec. 6	5 (d)	D-618 Procedure A	ft-lb/in of notch		
Haze and Luminous Transmittance	D-1003 Procedure A	Optional; Compression (see Note 3), transfer or injection	$\frac{1}{8} \times 4$ disc	—	per cent		
Thermosets							
Thermoplastics							
Index f Refraction	D-542	Optional; Compressi n	$\frac{1}{8} \times 4$ disc	—	—		

Thermosets Thermoplastics	Refractometer Method	(see Note 3), transfer or injection			
Water Absorption	D-570 Methods A and D	Optional; Compression (see Note 3), transfer or injection	$\frac{1}{8} \times 2$ disc	D-570	per cent
Brittleness Temperature	D-570 (Motor-Driven Tester)	Optional; Compression (see Note 3), transfer or injection	$\frac{1}{4} \times 1\frac{1}{2} \times$ 0.075 thick	D-618 (see Note 5)	C_{50}
Coefficient of Linear Thermal Expansion	D-696	Compression (see Note 3)	—	D-618 Procedure B	C^{-1}
Deflection Temperature	D-648	Compression (see Note 3)	$\frac{1}{4} \times \frac{1}{2} \times 5$	D-618 Acc. to Material Specification	C or F at 264 psi Fiber Stress
Vicat Softening Point	D-1525	Compression (see Note 3)	$\frac{1}{8}$ thick	D-618 Procedure A	C
Flammability	D-635	Optional; Compression (see Note 3), transfer or injection	$\frac{1}{8} \times \frac{1}{2} \times 5$	D-618 Procedure A	in or in/min

1. Use latest ASTM revision.
2. Thicknesses are to be determined according to ASTM D-374-57, Method C.
3. Specimens to be compression molded (fully positive) unless otherwise specified by ASTM Material Specification. Method used must be stated.
4. Unless specified otherwise by appropriate ASTM Material Specification.
5. Slow cooling from 135°C to 50° C at the rate of 5°C/hr is permissible. (Birks & Rudin method, ASTM Bulletin December 1959)

* $\bar{x}$ = Arithmetic average of n determinations.

† σ = Standard deviation among n determinations determined as:

$$\sigma = \sqrt{\frac{\Sigma(\bar{x} - x)^2}{n - 1}}$$

Number of samples (batches) tested (n) should be a minimum of 35 in order to obtain statistically meaningful results.

3. At spacings comparable to those found in laminates, the axial stresses are of comparable magnitudes.

The technique developed in these studies has corroborated data found previously with the spherical pressure transducer. The stress level in the longitudinal direction of the glass fibers was provided. The major drawback in this program is that simple photoelastic analysis yields only the difference between two principal stresses and does not yield absolute stress values. This technique is being extended to examine the effect of multiple fibers, small-diameter fibers, and resin-glass interactions as the composite is loaded externally.

Preimpregnated Tackiness

An example of a property of the preimpregnated roving that directly influences the manufacturing process is tackiness, which is the degree of stickiness of the resin on the glass fiber strand. It is the measure of the adhesive force resulting when the impregnated roving is brought into contact with another material, such as the winding mandrel, or the cohesive force when contacting itself. The latter condition exists when one layer of roving is placed on another layer. One significant aspect of the tackiness of the roving is its influence on the ability to wind unusual or nongeodesic patterns.

The degree or level of tackiness is not easily measured. Preimpregnated roving that has a sticky feel when squeezed between two fingers can be said to be more tacky than material that feels "dry" to the touch. In order to describe the levels of tackiness by a numerical value, various test procedures have been devised. In one method, a low number indicates more tack than a higher number. The equipment consists of an inclined ramp and horizontal track. The ramp, inclined at 10 degrees, is approximately 18 inches long, and the track is 60 inches long. Both are made of "V"-shaped aluminum extrusion. The strands of roving are placed on the track about 0.375 inch from the point of the "V" and stretched tightly along the track by weights (4 pounds on each 20-end strand). A 0.750-inch-diameter steel ball is placed at a specified height on the ramp and allowed to roll down the ramp and along the track in contact with the roving under controlled temperature conditions. The distance the ball travels along the track is the measure of tackiness. This value is reported as a composite number such as 8-32. The first digit is the distance along the ramp the ball was allowed to travel. The second number is the distance along the track in contact with the roving and is the average

of five rolls (after an initial zero-in roll) over the same sample (18). The test is not an unusual procedure, for similar tests are in use for measuring the tackiness of preimpregnated fabric materials and paints.

Experiments have shown that the test is useful only on "fresh" or soft pliable roving that has a degree of tackiness that can be felt when the roving is gently squeezed between the fingers. Preimpregnated roving that has become hardened slightly retains wrinkles from the package which resist the travel of the rolling ball, and erratic readings are obtained. The measurement range of the test may be extended in either direction, low or high tackiness, by the distance the ball is allowed to roll down the inclined plane. This is comparable to changing scales by changing weights on a Rockwell hardness tester. However, the distance most often used is 8 inches up the inclined ramp.

NONDESTRUCTIVE TESTING

Hydrotests and static firing tests are generally used to evaluate wound units. Complete destructive tests can be performed in order to systematically evaluate those not destroyed. Proof testing is also conducted by applying single or multiple loads in order to predict final operational performance. When proof tests are conducted, the ultimate strength characteristics tend to be reduced.

As the destructive tests develop, old and new nondestructive techniques are being applied to wound units. They include radiographic, X-ray, corona, ultrasonic, beta ray, acoustic transmission, photoelastic (19), and potential fiber optics. A television X-ray imaging system utilizes small-diameter (1-inch) sensing vidicon camera tubes as a direct sensing medium for the penetrating radiation image (1). The resulting signal is amplified by means of a closed-circuit television system. It is reported that a 32-times magnification image on a 17-inch picture tube gives a good contrast and detailed resolution better than 0.0005 inch.

Different test methods are being used to detect corona in dielectric materials. Experiments at Westinghouse Electric Corporation show that void detections in filament-wound glass resin are feasible. Corona detection is being used in many applications in the electrical industry to control product quality and reliability. To examine filament-wound units for delamination or other flaws, it is necessary to design special electrodes. The configuration of the electrodes would depend on the size and shape of defect to be located. Basically, when high voltages are applied, corona-like discharges will occur in voids. Radio noise

or corona pulses occur as a result of high-frequency components in the current generated by the discharge.

Detection of moisture within a laminate can be considered a nondestructive test. The presence of water can indicate a void or weakening of the laminate. Professor John O. Outwater of University of Vermont has developed a probe which measures the loss factor of the material in a radiofrequency field. The loss-factor change is dependent on the amount of moisture and distance of moisture from the probe.

Radiographic

Work is being conducted on the application of tracer-radiography technique to reinforced plastics (20). This technique provides a means for determining the concentration and orientation of groups of reinforcements. The advantage of being able to inspect the reinforcements by radiography provides a means to assure quality control of the product. Lower design-safety factors can be used or it will become possible to reduce thickness and overall material costs.

The mechanical reliability and deformational behavior of a fibrous, reinforced composite wound structure are dependent on a variety of factors; for example, concentration and geometrical placement of fibers, continuity and straightness of fibers, and degree of void-freeness or displacement of resin. The quality of a wound structure is quite dependent on these factors (21).

The tracer technique is being developed principally to permit the use of a nondestructive test procedure. X-ray and gamma-ray radiography has been developed successfully for the detection of flaws, voids, and cracks in various materials such as steel. It has also been used successfully in detecting flaws and defects in massive nonmetallic materials of lesser density, such as cast solid rocket propellants. When used with steel reinforced concrete it reveals the position of each reinforcing rod.

Radiographic techniques have also been used for the inspection of fibrous reinforced plastics. The types of defects which can be observed include unbonded areas, resin cracks, resin-rich areas, presence of foreign materials, and uneven steps in reinforcements. Since the atomic numbers of the constituents of this type of material are so close, they provide very poor contrast, and in X-rays it is difficult to discriminate between fibers and resin. Even though these defects can be observed, it is difficult to interpret them.

The tracer technique incorporates the use of an opaque tracer thread

to reveal the approximate locations and orientations of groups of fibers. Two types of glass fibers are used in the manufacture of wound vessels. A high-density glass is used to produce a tracer thread. This is installed among the low-density yarns or rovings which constitute the main reinforcements of the structure.

The lead-silicate glasses offer a good contrast in density to the aluminum-calcium borosilicate glasses, the beryllia glasses, and the soda-lime glasses which are used in filament-wound vessels. Young's modulus of elasticity and the hardness of the lead-silicate glasses are somewhat less than those of the other glasses. Lead-silicate glasses' thermal and electrical insulation characteristics are approximately similar to the standard glasses.

The ovaloid shape and mode of reinforcement of the end of a vessel are specified on the basis of a mathematical theory. The resultant displacement of the fibers is such that they are spaced equally around the poles and are all under equal tension. Dislocations and unequal tensioning will reduce the mechanical efficiency of the unit. It is therefore valuable to know whether the reinforcements have been spaced equally around the poles and whether they are all taut.

Tracer threads properly located at intervals in the various windings will permit a very close estimate of the positions of the windings. If tracer threads can be installed without damage to the structure, an important quality-control testing device will become available.

Photoelastic

Photoelastic coatings have been developed to analyze homogeneous metals. They are now being used to detect and analyze surface strains on wound units under dynamic conditions. These surface strains are highly directional. Tests conducted (22, 23) reveal that both the direction of the principal surface strains and the areas of unusual stress can be studied.

When brittle coatings or electric surface strain gages are used, the tendency is to obtain only limited or uneven strain patterns. With the birefringent photoelastic coatings and a polariscope, the direction and magnitude of the principal strains and their directions can be measured over the coated surface. To obtain a moving stress pattern, a reflective polariscope is used. The unit is made reflective, then coated with a birefringent material.

As the stressed area expands, the changing color patterns can be recorded with a movie camera. The film will reveal specific information on rate of strains, pattern errors, resin cracks, and residual strains.

Beta Ray

The beta ray back-scattering technique is being used by some investigators to determine the percentage of glass and resin in a laminate. Aerojet-General Corporation, with the assistance of Magnaflux Corporation, uses strontium 90 as the beta source. This source has a penetration in the laminate of approximately 0.04 inch, which means that there is infinite thickness. This results in the back-scatter being independent of laminate thickness and in the fact that it is responsive to only the surface layer.

The back-scatter of beta rays can identify the quantity of materials by virtue of their atomic numbers. The beta particles are reflected or back-scattered by any material on which they impinge. Glass has a higher atomic number than the resin, which results in the back-scatter being higher for the glass. Consequently it is possible to determine the percentage of each element.

Equipment used in this test is the beta source, an ionization chamber detector, an integrating circuit, a direct current amplifier, and a measuring bridge. This device permits determining the resin to glass content within plus or minus 2 per cent. The device is applicable and useful both after the filament-wound unit is manufactured and during wind-up. For example, it can be used to monitor and/or control resin content when it is first applied to the reinforcement.

Fiber Optics Nondestructive Testing

At the present time different systems are being studied as potential nondestructive testing techniques. One potential approach is to consider fiber optics. Light-transmitting glass fiber bundles in various configurations have been subjected to extensive optical, mechanical, and thermal testing for detecting hazards such as fire (23). They can also be applied in recording position changes in instruments for aerospace, ground, and underwater environments.

Fiber optics could conceivably be used to indicate expansion or creep of filament-wound structures. Theoretically the light intensity which is transmitted through the fiber will vary in accordance with the stress, elongation, etc., which occurs within the fiber. It is the science dealing with the transmission of electromagnetic radiation through transparent filaments which are long compared with their diameters. In its present development, which does not include application in filament-wound structures, the fiber diameters of interest are small enough to permit substantial bending without breakage. They allow the possibility of

flexible fiber bundles which can transmit light from one place to another along a curved path. Fiber diameters range from 1 to 10 mils. Smooth-walled transparent glass fibers or rods have the ability to conduct light from one end to the other by means of multiple internal reflections. This conduction phenomenon occurs even within narrow, flexible filaments of such materials, and moreover the filaments may be rather sharply bent without seriously reducing the light transmission.

EXPERIMENTAL TESTING

Experimental testing has never been more important than it is in the development of filament-wound structures, particularly in large cases. Design requirements are for the lowest weight compatible with reliability (7). There is also the need to predict with reasonable certainty the conditions under which these thin-wall cases will fail. In addition, the inevitable development time and cost must be kept to a minimum.

Only by anticipating the factors that cause theoretically unpredictable failure can optimum design be achieved without loss of time and

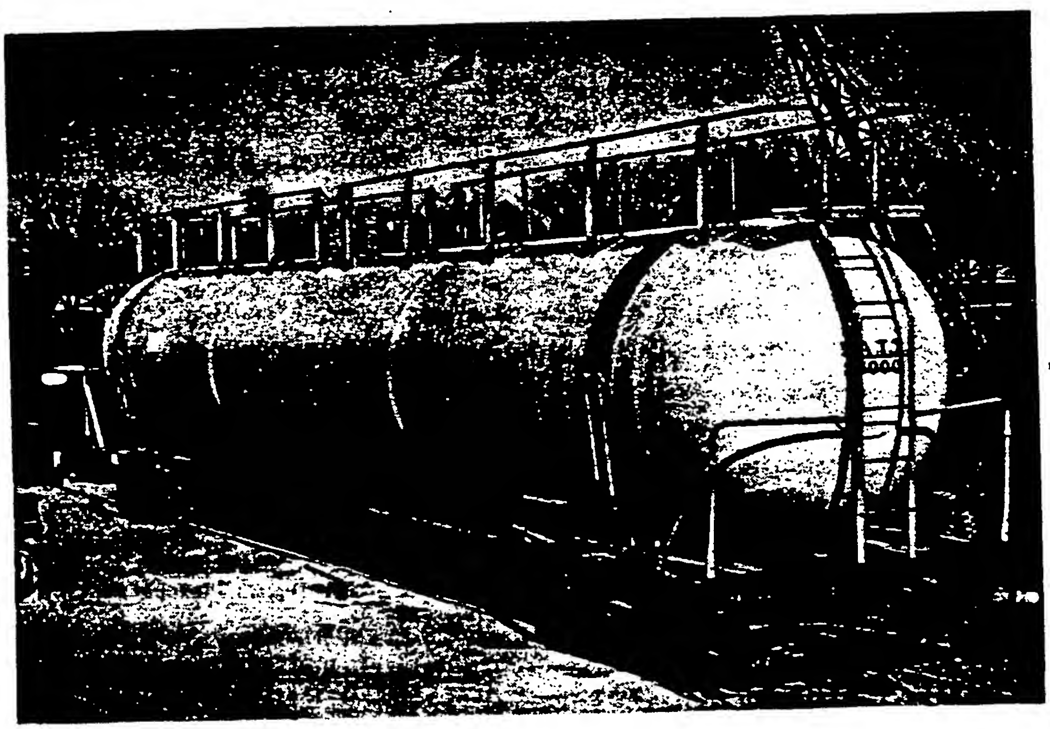


Figure 8.24 · Filament-wound 9-foot-diameter by 55-f ot-long railway tank car being subjected to impact testing. (Courtesy of Black, Sivalls and Bryson, Inc.)

money. Essentially, the more conventional rocket motor case is an all-metal isotropic pressure vessel. A large amount of data on the design of conventional metal pressure vessels is available. This type of data is not directly applicable to cases with high strength-to-weight ratios.

In order to achieve these ratios, the all-metal case must invariably be heat-treated to a high-strength level. At this level, material tends to behave unpredictably under the stress characteristic of case loads. This condition leads to notch sensitivity, which causes most case failures. Other factors in metal cases produce major problems, for example, minute cracks, inclusions and occlusions acting as stress raisers, abrupt changes in configuration, and basic metal material variables.

Designers have used theoretical stress analysis to reach some solution to these basic problems inherent with the new application for the metal case as well as the filament-wound case.

Quick and low-cost experimental tests generally involved conducting a hydrostatic test program. A limited number of sub-scale and full-scale cases in conjunction with an experimental stress analysis based on strain gauge results provides the experimentally desired test results.

The purpose for reviewing briefly the subject of conducting experimental testing on cases is to indicate the severe problem presently existing with the all-metal high-strength–low-weight structure. It has been predicted that in the future the majority of rocket motor cases will be made of glass-filament-wound structures, since more efficient structures can be produced and improved reliability can be achieved.

BASIC TESTS (24)

The following definitions apply to this section.

Ultimate strength. Obtained by dividing the maximum test load by the original laminate cross-sectional area.

Ultimate strength based on glass area alone. Determined by dividing the maximum test load by the cross-sectional glass area which carries the applied area.

Modulus of elasticity. A measure of stiffness of a material.

Apparent modulus of elasticity. The slope of the straight line portion of the load versus deflection curve converted to stress and strain is used to determine the apparent modulus. In the case of LC (fibers consist of longitudinal and circumferential windings) wound specimens several values may be desired, based on the entire wall thickness and on the longitudinal or circumferential glass area.

Secant modulus of elasticity. Obtained by dividing stress by strain at a specified stress or strain (usually at 70 per cent of stress).

Proportional limit. The point at which stresses cease to be proportional to strains. The proportional limit at 0.01 per cent offset is the stress at the point where a line parallel to the initial modulus and offset along the abscissa 0.0001 inch/inch, or 0.01 per cent strain, intersects the stress-strain curve.

Yield strength. The stress at the point in which a line parallel to the initial modulus line and offset 0.002 inch/inch or 0.2 per cent strain along the abscissa, intersects the stress-strain curve is the yield strength at 0.2 per cent offset.

Per cent elongation. Determine by strain gages, or with an extensometer over a 2-inch gage length, immediately before fracture and expressed as a percentage.

Per cent deflection. Determined by strain gages, or with an extensometer over a fixed gage length, such as 2 inches.

Symbols

A = area
b = width
c = distance to extreme fiber
D = diameter
d = depth
E = modulus of elasticity
I = moment of inertia
L = overall length
l = span
M = bending moment
P = load
p = pressure
r = radius
S = stress, strength
t = wall thickness
Δ = change, deflection
ϵ = strain
μ = Poisson's ratio
R = traverse feed-inches per mandrel revolution
n = number of glass fiber ends in roving used in hoop layers
y = number of hoop layers
HM = head moment
X = distance from center of pin to edge

Subscripts

avg = average
b = bearing
c = compressive
f = flexure
h = hoop, circumferential
i = interlaminar or inner
l = longitudinal
max = maximum
o = outer
r = radial
s = shear
t = tensile
u = ultimate, maximum sustained
g = cross-sectional area of single glass fiber
Y = mid-point
p = pin

Flat Specimens

Flat specimens are generally prepared from filament-wound sheets made on flat-type molds. Standard tests can be conducted on machined specimens in accordance with the following methods.

Property	ASTM Method	Federal Specification L-P-406 Method
1. Tensile	D-638	1011
2. Compression	D-695	1021.1
3. Flexure	D-790	1031
4. Shear		

(a) Interlaminar shear (plywood type), method A (Figure 8.25). Usual size specimen used is $L = 3\frac{3}{4}$ inches, $d = \frac{1}{4}$ inch, $b =$ 1 inch, $A_s = \frac{1}{2}$ inch^2 and $X =$ 1 inch.

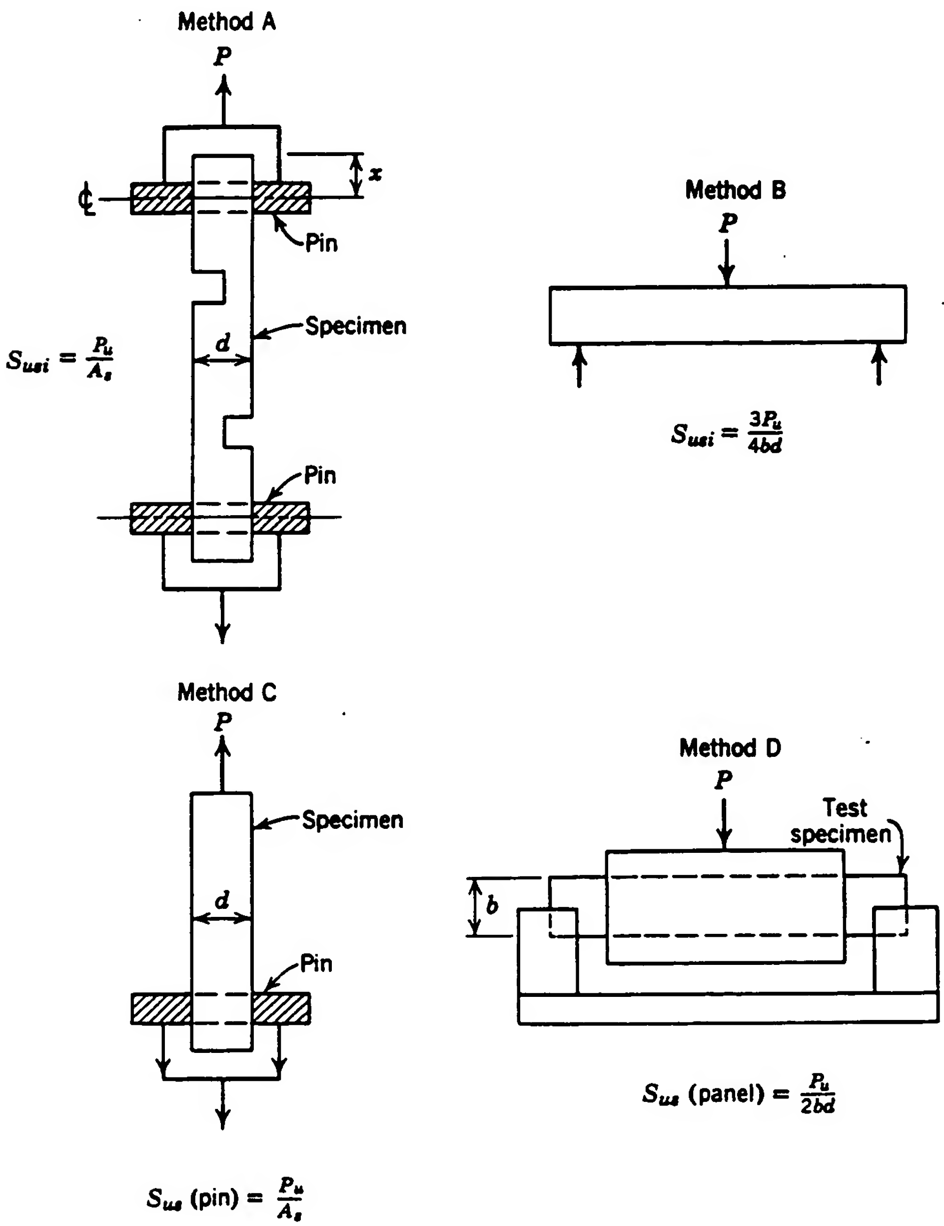
(b) Interlaminar shear, method B (Figure 8.25). Usual size specimens used are $l = 4$ inches, $b = \frac{3}{4}$ inch, and $d =$ various or $l =$ 1 inch, $b =$ 1 inch and $d = \frac{1}{8}$ inch.

(c) Pin shear, method C (Figure 8.25). Usual size specimen is $L = 4\frac{1}{2}$ inch, $b = \frac{3}{4}$ inch, $d = \frac{1}{8}$ to $\frac{3}{8}$ inch, end distance (to C.L. of pin) $= \frac{1}{4}$ inch, $D_{\text{pin}} = \frac{1}{8}$ inch, and $A_s = 0.404d$.

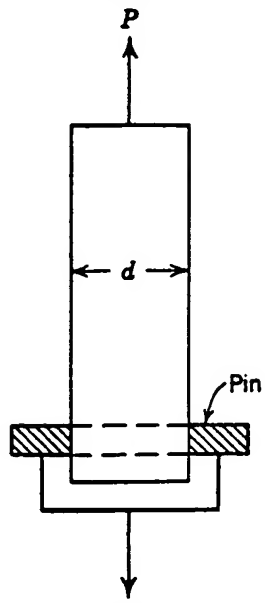
(d) Panel sh ar, m thod D (Figur 8.25). This t st is similar to the Johnson double shear test (L-P-406, m thod 1041). Usual size

of sp cim n is L = 6 inches, b = 1 inch, d = ⅛ to ⅜ inch, distance betw en supports = 4 inches, and width f shearing plug = 3 inches.

5. Bearing (Figure 8.26). Usual size specimen is L = 4½ inches, b = ¾ inch, d = ⅛ inch, D_{pin} = ⅛ inch and end distance (to C.L. of pin) = ⅝ inch.

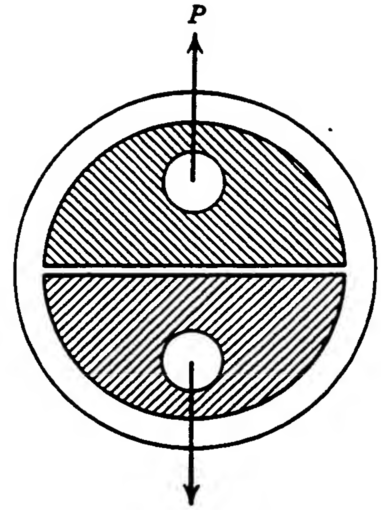


Figur 8.25 Shear tests (methods A, B, C, and D).



$$S_{ub} = \frac{P_u}{D_{pin}(d)}$$

Figure 8.26 Bearing test.



$$S_{ut} = \frac{P_u}{2bt}$$

Figure 8.27 Ring mechanical tensile test.

Ring Specimens

1. *Tension*
   (*a*) Mechanical method (Figure 8.27)
   (1) In this test two steel "Dee" plates are placed inside the ring, and load is applied as shown.
   (2) Surfaces of contact are lubricated.
   (3) In one laboratory the "Dees" are cut back to expose somewhat more than 2 inches of unsupported ring length, an extensometer is mounted on one of these unsupported lengths, and modulus is calculated from the equation

$$E_t = \frac{P}{2bt\epsilon}$$

where ϵ is taken as the measured change in length divided by the extensometer gauge length.
(4) In another laboratory the "Dees" used are as shown in the sketch. Head movement (taken as the distance between the "Dees") is measured, and modulus is calculated from the equation

$$\frac{\frac{P}{2bt}}{\frac{\Delta_e}{\pi D_{\text{avg}}}}$$

where e is twice the distance between the "Dees."

(5) A third laboratory cuts a $\frac{1}{8}$-inch notch in the inner circumference of the specimen and conducts the test with the notch positioned away from the "split" in the "Dees." This is done to eliminate bending and to assure failure at the notched section. The specimen is 1 inch wide; E and μ are determined by means of electrical resistance strain gauges bonded to the specimen.

(6) Specimens which have been used:

(a) $D_i = 5\frac{3}{4}$ inches $\quad b = \frac{1}{4}$ inch $\quad t = \frac{1}{8}$ inch

(b) $D_i = 9$ inches $\quad b = \frac{1}{2}$ inch $\quad t = \frac{1}{8}$ to $\frac{3}{8}$ inch

(c) $D_i = 6$ inches $\quad b = 1$ inch $\quad t =$ various amounts

(b) Hydrostatic pressure method (Figure 8.28)

(1) In this method, an elastomeric liner is placed inside the ring and the assembly is subjected to increasing hydrostatic pressure to the point of failure.

(2) The thickness dimension t is small, so that the specimen may be treated as thin walled.

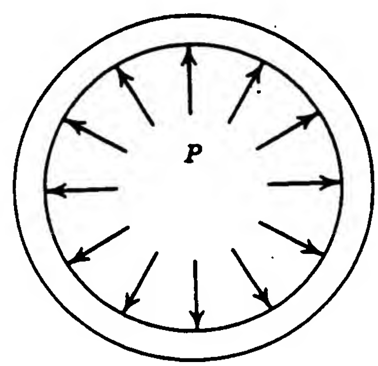
(3) Strain is determined by:

(a) wrapping a wire around the outer circumference of the specimen and noting the change in circumferential length:

$$\epsilon = \frac{\Delta_l}{\pi D_{\text{avg}}}$$

(b) an electrical resistance strain gauge mounted on the outer circumference.

(4) Specimens which have been used:



$$S_{ut} = \frac{P_u D_i}{2t}$$

$$E_t = \frac{p D_i}{2t\epsilon}$$

Figure 8.28 Ring hydrostatic tensile test.

$D_i = 5\frac{3}{4}$ inches, $b = \frac{1}{4}$ inch, $t = \frac{1}{8}$ inch

(c) Interlaminar tension (Figure 8.29)
 (1) The ring is bonded to two metallic discs and load is applied as shown.
 (2) Specimens which have been used:

$$D_i = 5\tfrac{3}{4} \text{ inches}, \quad D_o = 6 \text{ inches}, \quad b = \tfrac{1}{4} \text{ inch}$$

2. *Compression* (Figure 8.30)
 (a) Method A
  (1) Surfaces of contact are lubricated.
  (2) Strain is determined by measuring head movement and calculating from the equation

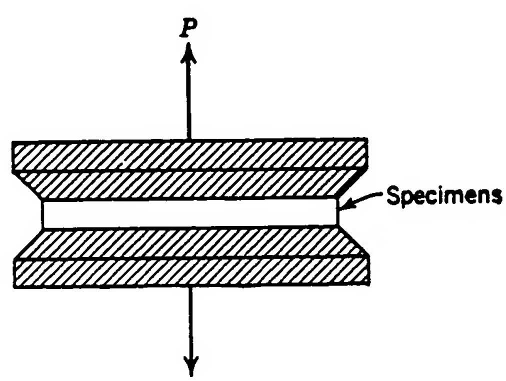
$$\epsilon = \frac{HM}{\dfrac{D_{avg}}{2}}$$

  (3) Specimens which have been used:

$$D_o = 6 \text{ inches}, \quad b = \tfrac{1}{4} \text{ inch}, \quad t = \tfrac{1}{8} \text{ inch}$$

 (b) Method B
  (1) This method has been used to determine modulus of elasticity in compression (see following section on flexure).
  (2) Specimens which have been used:

$$D_i = 5\tfrac{3}{4} \text{ inches}, \quad b = \tfrac{1}{4} \text{ inch}, \quad t = \tfrac{1}{8} \text{ inch}$$



$$S_{uti} = \frac{4P_u}{\pi(D_0^2 - D_i^2)}$$

Figure 8.29 Ring interlaminar tensile test.

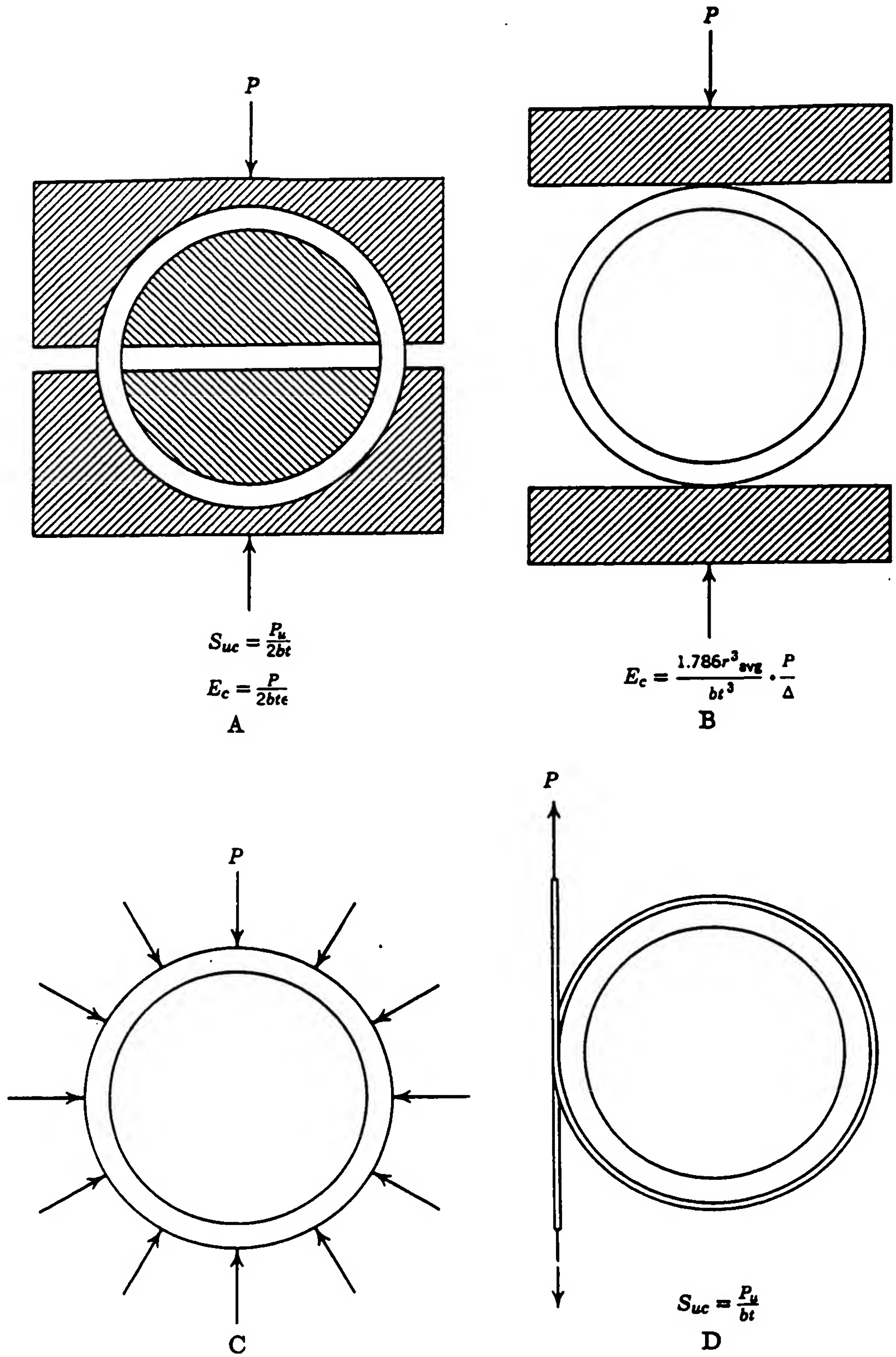


Figure 8.30 Ring compression tests (methods A, B, C, and D).

(*c*) Hydrostatic pressure method C

(1) In this test an elastomeric sealing ring is fitted over the specimen and external hydrostatic pressure is applied to failure.

(2) A thin-walled ring will fail by buckling (elastic instability) according to the following equation (25):

$$p' = \frac{3EI}{r^2_{avg}}$$

where p' critical collapsing pressure.

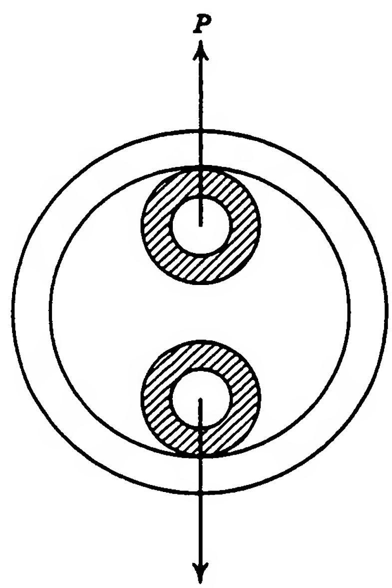
(3) Proposed specimen: $D_i = 6$ inches, $b = 1$ inch, $t =$ thick enough to prevent instability failure.

(*d*) External strap method D

(1) In this method a steel strap is wrapped around the ring, and a slot and tongue arrangement at the crossover point of the strap permits a complete wrap. Load is applied to the ends of the strap, putting the ring in uniform compression. Contacting interface areas are lubricated, and a shim is inserted at the crossover to prevent bending at this point.

(2) Specimens which have been used:

$$D_i = 5\tfrac{3}{4} \text{ inches}, \quad b = \tfrac{1}{4} \text{ inch}, \quad t = \tfrac{1}{8} \text{ inch}$$



$$S_{uf} = \frac{1.91 P_u r_{avg}}{bt^2}$$

$$E_f = \frac{1.786 r^3_{avg}}{bt^3} \cdot \frac{P}{\Delta}$$

Figure 8.31 Ring mechanical flexure test.

3. *Flexure* (Figure 8.31)
   (*a*) Specimens which have been used:

$$D_i = 9 \text{ inches}, \quad b = \tfrac{1}{2} \text{ inch}, \quad t = \tfrac{1}{8} \text{ inch to } \tfrac{3}{8} \text{ inch}$$

$$D_i = 6 \text{ inches}, \quad b = 1 \text{ inch}, \quad t = \text{various amounts}$$

4. *Shear* (Figure 8.32)
   (*a*) Interlaminar (Circumferential) method A
      (1) Surfaces of contact are lubricated.
      (2) Notches are cut with depth of $\frac{1}{2}t$ or slightly more.
      (3) In a variation of this method, two pairs of notches located diametrically opposite one another, are cut in the ring.
      (4) Specimens which have been used:

$$D_i = 5\tfrac{3}{4} \text{ inches}, \quad b = \tfrac{1}{4} \text{ inch}, \quad t = \tfrac{1}{8} \text{ inch}$$

   (*b*) Interlaminar (Axial) method B
      (1) Specimens which have been used:

$$D_i = 0.289 \text{ inch}, \quad t = \tfrac{3}{8} \text{ inch}, \quad b = \tfrac{1}{8} \text{ inch}$$

Cylinder Specimens

1. *Tension* (Figure 8.33)
   (*a*) Ends of specimen are built up or reinforced, to prevent failure in grips.
   (*b*) Strain is measured directly with an electrical resistance strain gauge mounted on the specimen.
   (*c*) Specimens which have been used:
      (1) 3-inch-diameter cylinders
      (2) $L = 15$ inches, $D_i = 3$ inches, $t =$ various amounts.
2. *Compression* (Figure 8.34)
   (*a*) Cylinder ends are built up or reinforced to prevent crushing at bearing surfaces.
   (*b*) Strain is followed by (1) head movement, (2) compressometer mounted on specimen, or (3) electrical resistance strain gauge bonded to specimen.
   (*c*) Specimens which have been used:
      (1) $L = 3.3$ inches, $D_i = 3.7$ inches, $D_o = 3.5$ inches.
      (2) 3-inch diameter cylinders.
      (3) $L = 3$ inches, $D_i = 3$ inches, $t =$ various amounts.
      (4) $L = 2$ inches, $D_i = 6$ inches, $t =$ various amounts.

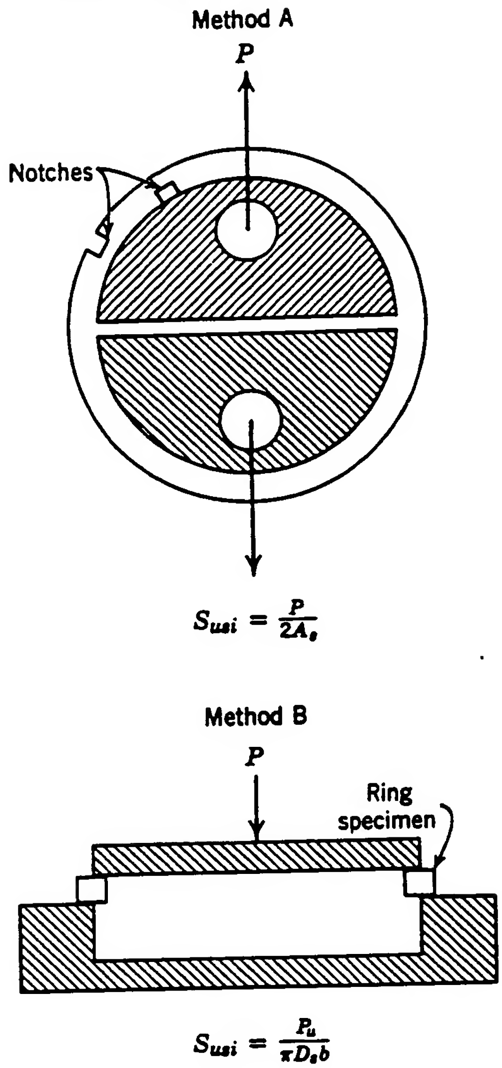


Figure 8.32 Ring shear tests (methods A and B).

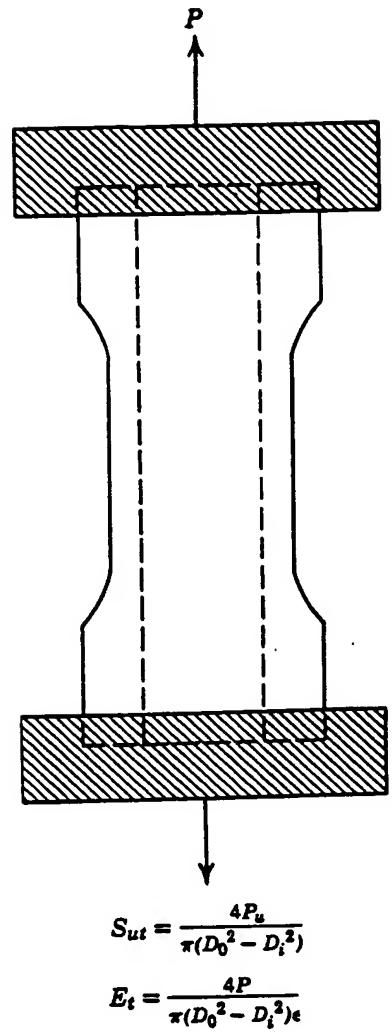


Figure 8.33 Cylinder tensile test.

3. *Flexure* (Figure 8.35)
   (*a*) Simple beam, method A
      (1) Specimens which have been used:

$$l = 18 \text{ inches}, \quad D_i = 1 \text{ inch}, \quad D_o = 1\tfrac{1}{8} \text{ inches}$$

   (*b*) Pure Bending, method B
      (1) This test is conducted by applying a couple to the end of the cantilevered specimen through a lever system.
      (2) In the reference reviewed, geometry of specimen and t/r ratio was selected so that failure occurred by buckling.

(3) Applicable equations:

$$S = \frac{Mc}{I}$$

where $c = r_0$

$$I = \frac{\pi}{64}(D_0^4 - D_i^4) \quad \text{in the general case}$$

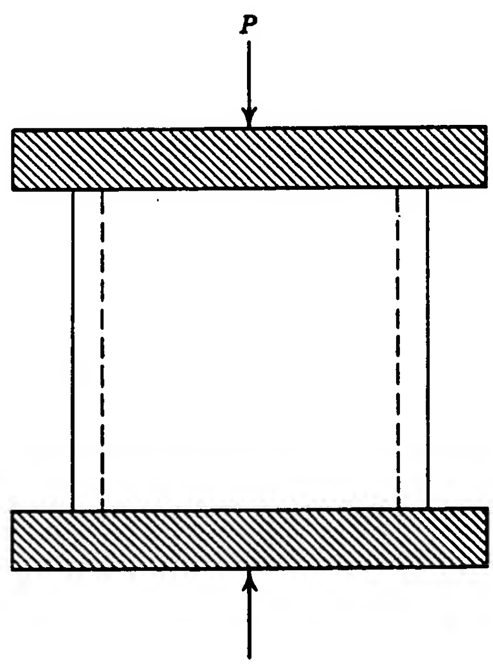
$$= \pi r^3 t \quad \text{for very thin annulus}$$

$$M' = K\frac{KE}{l - \mu^2} rt^2$$

where M' = critical bending moment causing buckling.

(4) Specimens which have been used:

$L = 18$ inches, $D_i = 4$ inches, $t = \frac{1}{8}$ inch (approx.)

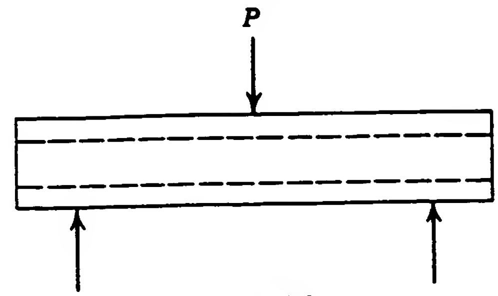


$$S_{uc} = \frac{4P_u}{\pi(D_0^2 - D_i^2)}$$

$$E_c = \frac{4P}{\pi(D_0^2 - D_i^2)\epsilon}$$

Figur 8.34 Cylinder compression test.

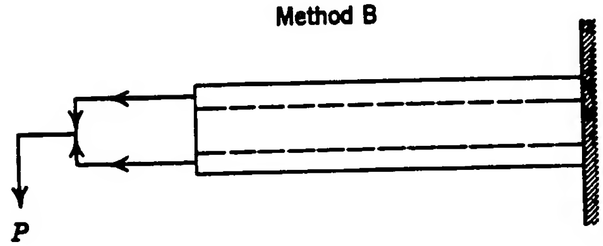
Method A



$$S_{uf} = \frac{M_u C}{I}$$

$$E_f = \frac{Pl^3}{48 I \Delta_y}$$

Method B



$$I = \frac{\pi(D_0^4 - D_i^4)}{64}$$

$$M_u = \frac{P_u l}{4}$$

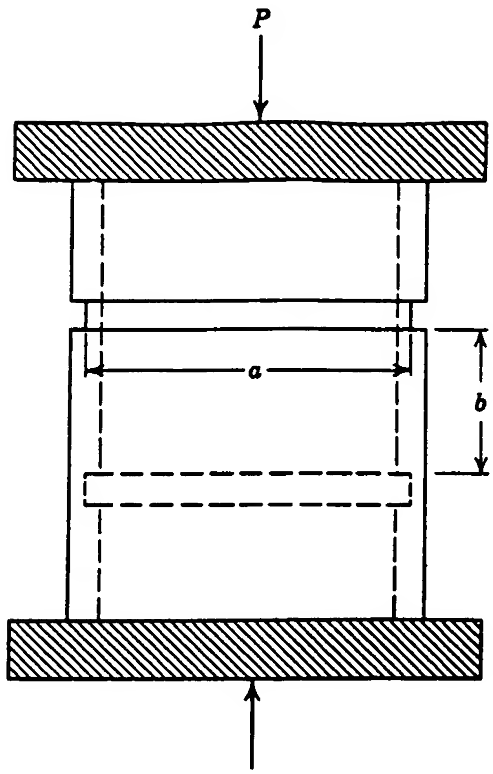
$$C = \frac{D_0}{2}$$

Figure 8.35 Cylinder flexure tests (methods A and B).

4. *Shear* (Figure 8.36)
   (*a*) *Method A*
   (1) Grove machined from outside and grove machined from inside surfaces.
   (2) Specimens which have been used:

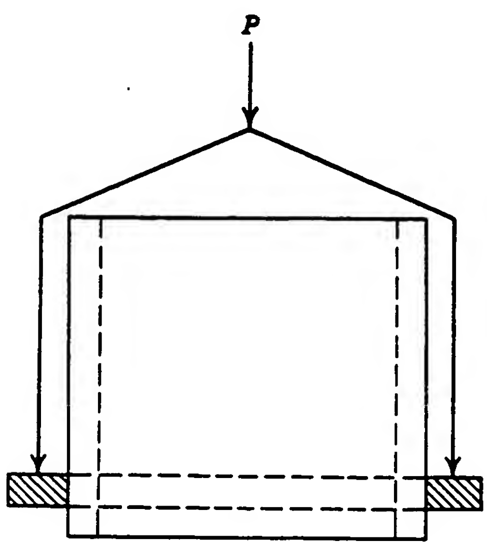
   L = 3 inches, D_i = 3 inches, t = various amounts

   (*b*) *Method B*
   Shear (interlaminar, axial) is also determined on cylinders in a manner similar to that described for rings Section 4 (b).
5. *Bearing* (Figure 8.37)
   (*a*) In a variation of this method, two diametrically opposed semicircular grooves are cut into one end of the cylinder, and load is applied to a pin which fits into these grooves.



$$S_{usi} = \frac{P_u}{A_s} = \frac{P_u}{\pi(ab)}$$

Figure 8.36 Cylinder shear test.



$$S_{ub} = \frac{P_u}{2t(D_p)}$$

Figure 8.37 Cylinder bearing test.

(b) Bearing stress may also be noted at 4 per cent deflection (Ref: L-P-406 Method 1051)

(c) Specimens which have been used:

(1) 2-to-3-inch diameter cylinder, ⅛-inch pin.

(2) D_i = 3.3 inches, L = 2.8 inches, t = various amounts, D_{pin} = ½ inch (applied to end).

6. *Buckling*

(a) This is a compression test on long, thin-walled cylinders, which fail by buckling. Load is applied on ends of cylinder.

(b) Details of the test are not given. The following pertinent equation is given (25):

$$S' = \frac{E}{\sqrt{3}\cdot\sqrt{l-\mu^2}}\cdot\frac{t}{r_{avg}}$$

where S' = critical stress at which buckling occurs.

This is a theoretical equation for thin cylindrical tubes but it is noted that buckling usually occurs at stresses well below this value due to imperfection in the cylinder, eccentric loading, etc.

(c) Specimens which have been used:

$$L = 18 \text{ inches},\quad D_i = 4 \text{ inches},\quad t = \tfrac{1}{8} \text{ inch}$$

7. *Torsion*

(a) In this test a cylindrical specimen is subjected to pure torsion, strain being measured with a special electrical transducer.

(b) Details of the test are not given. The following equation would apply.

$$S_{s_{max}} = \frac{2T_u r_o}{\pi(r_o^4 - r_i^4)} \quad \text{at outer boundary}$$

$$\theta = \frac{2Tl}{\pi(r_o^4 - r_i^4)G}$$

where T = twisting moment

l = distance between grips

G = modulus of rigidity (shear modulus)

θ = angle of twist

(c) Note that long, thin-walled tubes may fail by buckling when tested in torsion.

(d) Specimens which have been used:

$$L = 12 \text{ inches},\quad D_o = 2 \text{ inches},\quad D_i = 1.4 \text{ inches}$$

$$l \text{ (between grips)} = 3 \text{ inches}$$

Hydrostatic T sts n Cylinders

1. *Discussion*

(*a*) General (24)

Internal hydrostatic pressure tests are conducted in many laboratories on wound structures of various geometries, including cylinders, spheres, and other shapes.

(*b*) Fundamentals (Figure 8.38)

As shown in Section 1, when the vessel is subjected to internal hydrostatic pressure, an element in the wall (2) may be considered as subjected to a triaxial stress system, for example, S_h = hoop, or circumferential; S_l = longitudinal; S_r = radial. If the cylinder is thin walled ($t < \frac{1}{10}r$), the radial stresses may be neglected and the hoop and longitudinal stresses may be considered as uniformly distributed through the wall thickness.

The simple analysis just given applies to external as well as internal pressure conditions (with directions of stress reversed).

However, external pressure tests are complicated by the fact that failure may occur by elastic (or inelastic) instability. In thick-walled cylinders, the assumptions made in the thin-walled case, particularly with respect to stress distribution in the cylinder wall, do not apply.

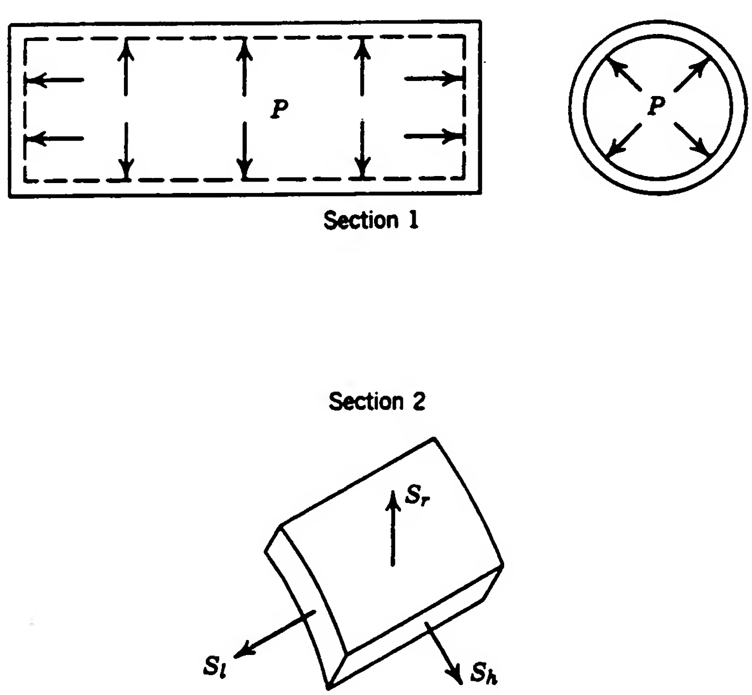


Figure 8.38 Cylinder hydrostatic hoop test.

2. *Internal Pressure, Hoop Tension* (Figure 8.39)
   (*a*) A cylinder is fitted with end plugs and tested with internal hydrostatic pressure to burst. The use of plugs eliminates axial loading so that stresses are essentially circumferential.
   (*b*) Cylinders may be wound on an integral internal liner, or liners may be provided after fabrication.
   (*c*) Strain caused by water or oil pressure may be determined by means of electrical strain gauges bonded to the outer or inner wall, or both.
   (*d*) Specimens which have been used:
      (1) L = 6 inches, D_i = 3 inches, t = ⅛ inch.
      (2) L = 6 inches, D_i = 2.89 inches, t = various amounts.
      (3) L = 6 inches, D_i = 3 inches, t = 0.06 inch ± 0.01 inch.
      (4) Many other geometries.

3. *Internal Pressure, Biaxial Tension* (Figure 8.38)
   (*a*) For thin-walled vessels:

$$S_{uth} = \frac{p_u D_{avg}}{2t} \quad \text{(hoop failure)}$$

$$S_{utl} = \frac{p_u D_{avg}}{4t} \quad \text{(axial failure)}$$

$$E = \frac{S}{\epsilon}$$

   (*b*) Test vessel is a closed, thin-walled cylinder which is subjected to internal hydrostatic pressure.
   (*c*) End closures may be of different shapes and may be wound integrally (with or without inserts), or may be plugs or caps of various types, bonded or screwed on to the ends of the cylinder.
   (*d*) If the ultimate strength in hoop is desired for the hoop area winding alone in LC specimens, the value of t is changed accordingly (26).
   (*e*) For determining the ultimate hoop strength in LC wound specimens based on the glass area carrying the load, the following equation is used:

$$S_{uth} = \frac{P_u D_{avg} R_h}{2nYA_g}$$

   (*f*) Based on glass area in longitudinal direction (for LC specimens):

$$S_{uth} = \frac{P_u (D_{avg})^2 \pi}{4R_l A_g}$$

(g) Specimens which have been used:

(1) D_i = 3 inches, I = 11 inches, t = various amounts.

(2) D_i = 6 inches, I = 11½ inches, t = various amounts.

(3) D_i = 18 inches, I = 24 inches, t = various amounts.

4. *External Pressure Tests* (Figure 8.39 except with external load)

(a) The following pertinent equations may apply in this type of test (25).

(1) For thin vessels, external collapsing pressure:

$$p' = \frac{t}{r_{av}} \frac{S_y}{1 + 4(S_y/E)(r_{av}/t)^2}$$

where S_y = compressive yield point of the material.

This equation is for nonelastic failure and holds only when $p'\left(\frac{r}{t}\right)$ is greater than the proportional limit.

(2) Thin-walled tube under uniform lateral external pressure (no longitudinal stresses in tube):

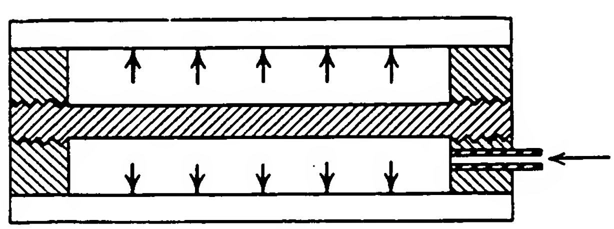
(a) Very long tube with free ends

$$p' = \frac{1}{4} \frac{E}{l - \mu^2} \frac{t^3}{(r_{av})^3}$$

where $l = 4.90 r_{avg} \sqrt{\frac{r_{avg}}{t}}$

(b) Short tube, ends held circular, approximate equation:

$$p' = 0.807 \frac{Et^3}{l(r_{av})^2} \sqrt[4]{\left(\frac{1}{1 - \mu^2}\right)^3}$$



$$S_{uth} = \frac{P_u D_{avg}}{2t}$$

$$E_t = \frac{p D_{avg}}{2t\epsilon}$$

Figure 8.39 Cylinder hydrostatic biaxial test.

(b) Specimens which have been used:

(1) $L = 11\frac{1}{2}$ inches, $D_i = 6$ inches, $t =$ various up to $\frac{1}{2}$ inch.

(2) $L = 5$ feet, $D_i = 31$ inches, $t = 1.6$ inches.

(3) Ring-stiffened cylinders.

5. *Thick-Walled Cylinders*

(a) Some experimental work has been done in which tests are performed on thick-walled cylinders (25).

Test Procedures

Standardization of test procedures is gradually developing within the filament-winding industry in order to meet specific requirements. With this relatively new industry there is the usual condition of developing reliable test procedures for raw materials, manufacturing procedures, and cured parts. Tests described in this chapter as well as in other chapters can be useful in developing standards for specific applications.

A very important aspect to consider is the size and shape of specimens. It is to be expected that changes in these categories generally have different end results. Growth of setting up standard tests for

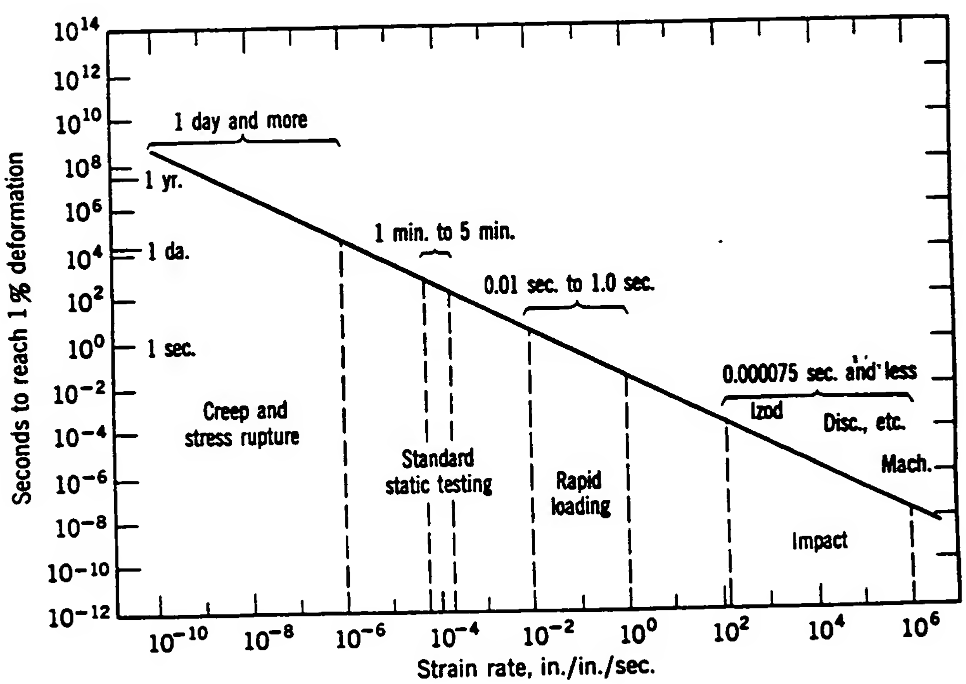


Figure 8.40 Relation of rapid loading strain rates to those developed in other methods of tensile testing.

flat reinforced plastics can be used as guides. Examples included various test methods used in conducting compression tests on thin sheet material (27) and miniaturized ASTM test specimens (28). Other aspects to consider include rate of loading. Figure 8.40 shows a comparison of rate of strain loading with various methods of conducting tensile tests.

QUALITY CONTROL

Filament winding control provisions are primarily concerned with three basic areas: (1) materials, (2) processing or fabrication, and (3) quality assurance in the finished article. There are infinite combinations of detailed variables, however, such as the following.

Raw material. Resin (type, pot life, wettability, tack, flexibility, etc.), reinforcement (grade, construction, package, etc.), monomers, catalyst, fillers, mold releases, pigments, and sizing.

Processing. Wet or dry technique, mandrel, equipment technique, tensioning, shape of part, curing cycles, molding temperatures, mold pressures, post cure, void content, resin content, winding pattern, and speed of winding.

Quality assurance. Destructive versus nondestructive testing, mechanical tests (tensile, compression, impact, etc.), physical property (density, thermal coefficients, etc.), environmental exposure (weatherability, chemical resistance, pressure cycling, etc.), packaging, and flame retardness.

These many combinations of variables have advantages and disadvantages. The greatest advantage is that the designer, fabricator, or user can program different characteristics in the end item. Ironically all these programmed variables develop problems. Controls and/or tests have to be established for each variable. In certain cases the controls may not be available (or understood), accuracy may not be sufficient (or applicable to production techniques), or controls cause the costs of end items to be excessively high.

As more filament-wound parts either replace industry metal parts or independently find new applications, techniques in quality control are developed and/or improved. This growth pattern in the filament-winding industry is a healthy condition and typifies other industries. As is expected in any profitable and growing industry, there is always the requirement to obtain applicable and upgraded controls and tests.

The following description of setting up control procedures typifies industries' approach. This procedure has been determined by the Allison Division of General Motors Corporation (29) to be useful.

This review compares the filament procedures with those being used in producing steel cases for the Minuteman missile.

Materials

The initial materials quality control operation for reinforced plastic cases is that of receiving inspection of the constituents of the resin system. Vendor affidavits are checked, and the materials are reviewed to assure that they comply with the specification requirements. The resin system constituents are used to formulate a test batch for each lot of each component. The room-temperature viscosity and the gell time at 212°F is determined, and the formulated system is cast into flat panels and cured. Flexural and shear samples are machined from the cured panel and tested at room temperature and at 300°F. Batches that comply with the appropriate, previously established Engineering Materials Specification (EMS) are placed in special stores for future use.

In addition to resin components review, each spool of roving for use in fabricating filament-wound cases is reviewed. Tensile strength, by a dry strand test; yield, in yards per pound; and binder content, by a burnoff test, are determined in comparison to the appropriate EMS. The package build, ribbonization, catenary, and overall appearance are checked by visual inspection. Acceptable materials are placed in special stores for future use.

Material quality control operations for reinforced plastic cases thus include a review of:

1. Individual formulation constituents
2. The formulated system
3. Each spool of reinforcement

All these operations must be performed by the fabricator to assure ultimate quality.

The initial materials quality control operation for steel cases is a review of the composition and general structure of the alloy. In the case of D6 steel, this consists of qualification of the air melt master heat by chemical analysis, determination of structure, response to heat treatment and strength properties. Acceptable heats of material are then vacuum consumable electrode remelted and this final heat is qualified by analytical procedures, metallurgical property tests, and ultrasonic inspection. If acceptable the billets are used to forge the dome and cylindrical section blanks.

The material quality control operation for steel cases begins with

the basic constituents of the alloy and extends through the two melt operations. Because none of these operations or the subsequent forging operation are performed by the case fabricator, there are no separable material quality control problems for the fabricator. The receipt and review of forgings is covered in the fabrication process quality control section because the forging operation affects the physical properties of the material.

The essential differences in the steel and reinforced plastic materials quality control program is in who performs the tasks. Since the reinforced plastic case fabricator combines the materials to be used, the entire materials control program must begin there. In the steel case program, the final fabricator does not come into contact with the material until it has been semiprocessed. Therefore, there is no need for a separate materials quality control program.

Fabrication Process

The initial fabrication process quality control operation for reinforced plastic cases is that of checking the initial machine setup. This is performed by actually winding over the mandrel, then using appropriate devices to check ribbon width, spacing, pattern, and roving tension in comparison with the established Engineering Process Specification (EPS).

Following setup checkout, the mandrel and the impregnation system are cleaned in preparation for winding. The resin system constituents and the glass to be used for fabrication are obtained from stores. The resin constituents are mixed in the ratio established by the EMS, and the viscosity and gell time are determined as a cross check on proper formulation. After these tests the resin system is poured into the impregnation system feed tank. The approved glass is placed on the spool rack and the rovings are pulled through the system. Then the glass route and the impregnation setup are visually checked to assure compliance to the established standard.

After setup checkout and material installation, the first of four process control hoops is wound. These hoops are a 16-inch-diameter version of the NOL ring samples. They are wound before vessel helical winding, after vessel helical winding, before vessel hoop winding, and after vessel hoop winding. Thus a measure of any material degradation or process variation is obtained for future consideration.

After the first set of process control hoops are wound, the process status indicators on the machine console are set at zero position, and vessel winding is started. During winding of the first layer, process

status indicators are checked to determine whether the layer was completed in the precalculated machine passes. If not, the error can be calculated and a spacing adjustment made while running to offset the the setup error.

During the entire process the tension level of the ribbon is monitored by a precalibrated monitor-takeup roll. Also, the effect of tension on the mandrel is monitored by strain gages placed on the mandrel exterior. With these two methods of measuring tension it is possible to determine, while winding, the current preload of the glass and the cumulative effect of glass preload on the mandrel. If an excess mandrel strain rate is evident on the initial layer, the tension level of subsequent layers can be reduced using the ribbon monitoring device as an indicator, thus reducing mandrel strain and producing a more uniformly preloaded reinforcement.

Following winding, the vessel and process hoops are gelled on the winding machine using banks of heat lamps. The interior temperature of the vessel is monitored by thermocouples mounted at the vessel-mandrel interface. The exterior temperature of the vessel and hoops is monitored with a radiation pyrometer. Rate of heating, hold at temperature, and rate of cool-down are controlled by an EPS. Following the gell cycle, the vessel and hoops are cured in a large gas-fired oven. Both oven temperature and part temperature are carefully monitored.

After cure, the mandrel is removed and the vessel is visually inspected. Any post winding operations such as facing the skirts to achieve overall length, bonding in skirt inserts, etc., are then performed. Process hoops are tested and the data analyzed to predict vessel performance.

Fabrication process quality control for reinforced plastic motor cases covers:

1. The initial machine setup.
2. A final check of the resin formulation.
3. The status of the process in relation to fixed precalculated check points.
4. The tension in the glass reinforcement and the resultant effect on the mandrel.
5. The gell cycle.
6. The final cure cycle.

All pertinent quality data gathered during the process must be reviewed and used while the process is in operation, because when the winding operation is completed, the quality of the product is unalter-

ably determined. The process hoop data serves only to indicate the final quality of the structure. If inferior, the entire unit must be scrapped.

Fabrication process quality control for steel cases begins with coupons taken from the rough cylinder and dome forgings. Some of these samples are checked for chemical composition and are then heat-treated per the case heat-treating procedure. The strength and fracture toughness properties of these forgings are then determined using standard and center-crack tensile specimens machined from the coupons just described. Other samples from the forgings are used as process control samples and follow the case through actual heat-treating operations.

Forgings fulfilling established requirements are released for subsequent machining, roll forming, and stress relief. They are then inspected, dimensionally and by magnetic particle techniques.

Acceptable cylinder sections and end closures are automatically welded at controlled machine settings. The case is then stress relieved and inspected in the weld areas utilizing radiographic, fluorescent penetrant, and magnetic particle methods. If defects are evident in the weld area, they may be ground out and the part locally repair welded. If the entire weld is defective, the components can be machined apart and rewelded to produce an acceptable welded assembly.

After welding, the cases and process control samples are fully heat treated in accordance with laboratory forging qualification test results. Process control samples are then tested for tensile strength and fracture toughness. Following heat treatment, the case is inspected in the weld areas via radiographic and fluorescent penetrant methods and in all areas via magnetic particle techniques and standard dimensional methods. Any defects in the weld area are repaired by annealing the weld zone, repairing as required, annealing the entire case, then heat-treating and inspecting again. If acceptable, the case is finally machined in the skirt, closure joint, and port areas and dimensionally inspected.

Fabrication process quality control for steel cases covers:

1. Initial forging material characteristics.
2. Defect and dimensional review of finished machined components.
3. Defect review of all welds.
4. The effect of hardening and tempering cycles.

In all cases the data gathered need not be interpreted immediately and, in fact, if questions arise it can be rerun for further verification. The

initial control points are used to assure quality subcomponents. If defects exist, they can be discarded at a relatively low cost. Further, it is possible and permissible to repair weld-defect areas. The process control samples are used to predict the effect of the final heat-treating operation and therefore directly control the end product.

In comparing the two process quality control programs, it is evident that the most significant differences are the absence of any repair methods or component screening methods for the reinforced plastic cases. Furthermore, any quality control method for the reinforced plastic case must be performed and interpreted rapidly if the benefit is to be that of quality improvement rather than just screening of defective parts. The basic similarity between the two programs is the need for detailed process instructions.

Final Quality Control

After the reinforced plastic case has been inspected dimensionally and approved, it is pressure tested to a specified pressure level. Pressure is applied at a fixed rate and is held at the test value for a specified time, usually 60 seconds. The case is then reinspected dimensionally and visually for any physical changes. If none are evident, the case is deemed acceptable. Currently there are no methods being used to determine the probable performance limit or to determine hidden flaws which might cause failure upon repeated loading.

The steel case is pressure tested in the same manner as the plastic case. Following pressure test it is dimensionally inspected, visually inspected, and inspected by radiographic and magnetic particle techniques. Any flaws which might reduce operating capability are removed by grinding where stock permits. Weld-area flaws can be machined out and the case locally rewelded if necessary. Although it is rarely required, the final quality control operation for steel cases can indicate a need for repair and the repair can be made in order to save a finished assembly. Further, the characteristic of metals to yield at a value below the ultimate strength assures that if the pressure test load is near the ultimate performance capability of the case, the case will deform permanently. Any such deformation will be detected in the final inspection operation thus serving to assure performance in excess of the test conditions.

The essential differences in final quality control operations of reinforced plastic and steel cases is that the plastic case is not repairable should any defect be found, it is not readily adaptable to flaw-detection techniques used for metals, and it does not give an indication

of the proximity of test load to ultimate capacity. For these reasons, the general approach to the plastic case final control is to perform all operations possible on each case, then burst-test one of each series of cases in order to establish ultimate performance.

New Final Product Quality Control Technique

A new approach is being taken to the final product quality control problem of predicting the ultimate performance of a case after simple pressure test. This approach, which consists of lead-silicate glass tracers wound into the case and inspected under pressure by radiographic means, is currently being explored in the Allison Research Laboratories. If tests are successful, the technique will be used for large cases by winding one end of lead-silicate glass into the case during the winding operation. The case will be radiographically inspected under pressure. The lower-strength lead-silicate fibers should fail below the ultimate strength value of the actual case reinforcement. Therefore, if radiographic inspection at a given pressure indicates that failure has occurred, the probable performance limit of the case can be calculated, based on the relative strengths of the two glasses. If successful, this technique will alleviate the need to pressure test one of each series of cases to failure.

Basic Considerations for Quality Controls (30)

Most reported test work in filament winding has been aimed at providing realistic design data. Quality control procedures have, for the most part, been nonstandard and dependent on the individual facility. Obviously, in filament-wound products where maximum quality and reproducibility are required, quality and reproducibility of the materials used must be carefully controlled.

The purpose of this section is to describe the methods of quality control testing and interpretation of data employed by Aerojet-General Corporation, with particular regard to the manufacture of relatively thin-walled internal pressure vessels. Most of the tests involve application of stress to a specimen until complete failure occurs. The rate of loading selected was that required to produce a strain rate of 1 per cent per minute. Use of a consistent loading rate reduces variations in test methods and permits smaller sample size. Consequently this loading rate is used in all mechanical testing.

Quality control test methods fall into two broad categories: those designed for control of incoming raw materials and those designed to

evaluate reproducibility of quality of composite structures. Quality control tests are essential for evaluating glass reinforcements, epoxy resins, and preimpregnated rovings.

Although other filaments are in various stages of development, costs indicate that glass will be the major reinforcement for some time to come. Since the reinforcement serves as the primary load-bearing component, fiber quality is particularly critical. The package of the roving-fiber should not have any broken ends or loose fibers, should be relatively uniform in density and physical dimensions, and should be centered on the delivery tube so that fibers are not flush with ends of the core. Moreover, the fibers should be flat and continuous, under uniform tension, and the strands should not be twisted.

Whenever optimum performance is required, the end count—the number of parallel ends in the roving bundle—should be exactly as specified (zero ends "out"), 20 ± 0 ends. Formerly, testing of HTS-E glass roving in the "as-received" condition revealed crushing of filaments, fiber-to-fiber abrasion, and uneven tension among the strands causing sequential failure. In addition, values were much lower than those obtained for filament stress in simple composites such as the NOL ring, which has the advantage of placing the fiber in essentially a tensile stress field.

Accordingly, Aerojet-General developed the Aerorove Strand Test to overcome these difficulties. The roving is placed on a jig under slight tension which aligns fibers and provides uniform loading of all the fibers. A vinyl coating is then brushed on and cured. Following cure, six specimens, 14 plus or minus 0.5 inch long, are cut for testing on a tensile test machine. The coating locks the filaments in place, protects the filaments in the areas of jaws, and reduces the bearing of one strand directly on another.

Tensile Strength. This test measures the average tensile strength of the fibers in the roving. When they are properly prepared and tested, failure should occur in the specimen away from the edges of the grips. Fiber tensile strength, arrived at statistically, is to a large extent dependent on surface flaws and mechanical damage. These conditions vary from roll to roll as well as between two adjacent lengths within a single roll.

Random samples of all rolls of a given lot from a manufacturer are tested for tensile properties in compliance with MIL-STD-414. For the weight per linear yard, a random sample of 10 per cent of the lot is selected. This sample plan reduces the amount of laboratory testing required for acceptance, and has replaced MIL-STD-105 pre-

viously used by Aerojet-General. Variability of strength within a single roll has been studied, and they have adopted as a quality standard a minimum level of 280,000 psi for HTS-E roving and 400,000 psi for AF-994 roving. Recent commercial production has averaged 340,000 psi for HTS-E glass. Probably, the minimum acceptable level could be raised to 320,000 psi without any appreciable increase in the rejection rate.

Ignition Loss. The amount of material—per cent by weight—volatilized at ignition is a measure of the quantity of organic finish applied to the roving. It consists of both moisture and organic finish loss.

Weight per Linear Yard. The weight per unit length of the roving after ignition measures the dimensional uniformity of the fibers. Furthermore, it serves as an indirect measurement of the filament diameter control by the glass manufacturer. Random samples of 10 per cent of the lot are selected for this test.

Horizontal Shear Strength. This test determines the adhesion between the fibers and the organic finish. It may vary with specimen thickness, temperature, atmospheric conditions, and differences in the rate of loading. These specimens are conditioned in accordance with ASTM N-618.

Catenary. This test indicates the degree of uniformity of tensioning of the strands in the roving as applied by the manufacturer.

Resins. At present, epoxy resins are most widely used in filament winding because of their excellent adhesive properties, good resin-to-glass affinity (wetting), and low shrinkage during cure. In addition, epoxy resins are 100 per cent reactive; thus no volatiles are released during cure. Quality control procedures are employed to determine desired mechanical and processing properties of the resins and to provide acceptance criteria for incoming raw materials.

(*a*) *Mechanical properties.* Once the mechanical properties of a particular resin system have been obtained, they may then serve as a basis for quality control. Epoxies are characterized by tensile testing as described in ASTM D-638. Besides possessing high elongation and high tensile strength, a resin system should have the ability to resist the propagation of a crack. This is generally known as a toughness factor.

Specimens for a toughness factor test devised by Aerojet-General and the ASTM tensile strength elongation test are cut from a cast sheet and checked with procedures as described in ASTM. The sheet

is relatively thin to reduce exotherm and internal stress. Care should be taken to exclude the trapped air or other volatiles during the preparation of the sheet. Three of the specimens are cut from the center portion of the sheet to reduce edge effects. A small portion of every production resin batch mixed is cast into sheets, and the mechanical properties are determined to make sure there has not been an improper selection of ingredients or erroneous weighing.

(b) *Processing properties.* Perhaps even more important than mechanical properties are the working properties, which must be compatible with the manufacturing process. The resins system must have an adequate pot life to permit mixing and a reasonable period of storage before use. In addition, it should have a viscosity (usually between 200 and 1,000 cps) low enough to permit rapid and thorough wetting of the fiber.

It is frequently necessary to heat the resin pots to achieve this viscosity, and consequently viscosity versus temperature information is needed. A variation of the last test, increase of viscosity at a given temperature until gelatin or gel time, provides the basis of acceptance and indicates that a system is within the control limits.

(c) *Incoming raw materials.* Incoming resins and hardeners are evaluated by Aerojet-General with specially developed tests to insure uniformity and batch purity or adequacy of the max. For resins, tests include epoxide equivalent, hydroxyl content, and chlorine content. To help insure batch uniformity, viscosity is generally measured for liquid epoxy resins and melting point for solid epoxy resins. Another means of quality control is the use of infrared spectrophotometric analysis. It may be used to replace time-consuming analyses for epoxide, hydroxyl, and chlorine content.

Tests for epoxy hardeners are generally restricted to those needed to identify and insure purity. Such tests can include chemical assay, acid content, and tests for anhydrides, amine content, water content, melting or boiling point, particle size, viscosity, index of refraction, and specific gravity. For a particular hardener, only a few of these tests will be needed during acceptance testing. Though not in wide use, infrared analysis can serve as an expedient, thereby reducing the number of measurements that would otherwise be necessary.

With the mixed resin-hardener system, tests should be conducted to insure proper mixture ration, thorough mixing and blending, and ability to cure under specified conditions. These tests can cover viscosity and working life and selected mechanical strength properties of cured resin and resin-glass composite specimens.

Preimpregnated R vings. Prepreg rovings offer such advantages as more stringent quality control of material at an early stage of manufacture, a reduced tendency of the strands to slip when wound over sharply curved surfaces, and more rapid manufacture. Tests for prepreg should determine strength of the prepreg strand and the suitability of the prepreg for processing.

(*a*) *Tensile strength.* Prepreg strand is tested in much the same manner as the dry glass strand, except that no vinyl coating is employed and the prepreg is given a standard cure while on the test fixture. As in the case of the dry glass, this test serves as an excellent quality control device. The spread in strength data for the prepreg strand is slightly greater than that of the dry roving, and the average value is lower. This is attributed not to mechanical damage, which may occur in processing the prepreg strand, but to the absence of the vinyl coating which serves to protect the roving.

With prepreg strand, it is probable that there is an increased slippage and greater damage by crushing in the jaw. As a result, a larger percentage of failures occurs in the jaw when testing prepreg than in the testing of dry roving.

(*b*) *Other variables.* Other variables which form the basis for quality control of the prepreg strand are the resin content and degree of advancement of the resin. Standard procedures to determine control limits for these variables have not yet been established. One approach that shows promise involves extracting the soluble resin from the prepreg (before cure) in a dimethyl formamide extraction apparatus, and then measuring the viscosity of a known concentration of the extract.

Concentration of the extract is determined by refractive index at a given temperature. The viscosity of the extract is a function of the molecular weight of the resin, which, in turn, is a measurement of the degree of advancement. By this method, it has been possible to show differences in reactivity in prepregs which has taken place while stored at room temperature for only one day. A procedure is now being investigated to determine control limits before adopting it for production material.

Composite Structures. Although a manufacturer must know the mechanical properties of the materials used to make up a structure, he must also determine how these ingredients perform in the composite through the use of quality control procedures. The 4-inch specimen, NOL rings, horizontal shear and reliability tests give a sound basis for determining dependability of composites.

The biaxial specimen is a glass-filament-wound cylindrical pressure vessel with integrally wound heads which contain polar aluminum bosses. Preformed rubber cups, with aluminum boss inserts, are formed in halves, and these are then bonded under pressure to produce a sealed rubber bladder around a perforated steel mandrel or a plaster dissolvable mandrel.

Test specimens using a balanced design and constant processes and materials have been cylindrically burst and have exhibited a spread of 1 to 1½ per cent, as shown in Table 8.5.

The test is particularly useful for evaluating effects of broken filaments in incoming roving. Some such filaments are repaired by overlapping or butt joining, or are merely left separated. Table 8.6 shows a statistical plan by which effects of such repaired broken roving on composite strength can be evaluated. The numbers with letters refer to specimens taken from the indicated positions on a 4-inch specimen.

This test may also be employed to determine combined effects of prestress and humidity exposure. Tables 8.7 and 8.8, which summarize the results of such tests, show that the composite is weakened and that this degradation is accelerated by prestressing.

Table 8.5 *Chamber Control* (30)

Chamber Number	Burst Pressure, psi	Failure Area
1	2,900	Knuckle
2	2,850	Knuckle
3	2,850	Knuckle
4	2,975	Knuckle
5	3,075	Boss
6	3,150	Hoop
7	3,150	Knuckle
8	3,025	Hoop
9	3,125	Long-Head
10	3,250	Boss Hoop
11	3,025	Knuckle
12	3,050	Knuckle
13	3,115	Boss
14	2,900	Long
15	2,950	Hoop
16	3,025	Long
17	2,900	Hoop

Table 8.6 *Typical Statistical Plan for Effect of Cut Roving (30)*

	Single-Filament Cut			Two Adjacent Filaments Cut			Three Adjacent Filaments Cut		
	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3	Pos. 1	Pos. 2	Pos. 3
Cut Ends	1A	2A	3A	4A	5A	6A	7A	8A	9A
Overlapped	1B	2B	3B	4B	5B	6B	7B	8B	9B
Cut Ends	10A	11A	12A	13A	14A	15A	16A	17A	18A
Butt-Joined	10B	11B	12B	13B	14B	15B	16B	17B	18B
Cut Ends	19A	20A	21A	22A	23A	24A	25A	26A	27A
Separated	19B	20B	21B	22B	23B	24B	25B	26B	27B

P s. 1—innermost layer (next to boss).
Pos. 2—middle layer (60° away from boss).
Pos. 3—outer layer of hoop wrap.

Table 8.7 Pr stress Envir nment (30)

Chamber Number *	Environment	Hydroburst Pressure, psi
1	Control	2,900
2	Control	2,950
3	Prestress to 80% ultimate	3,025
4	Prestress to 80% ultimate	2,900
5	10-day 95% rh[b]	2,725
6	10-day 95% rh	2,740
7	Prestress to 80% ultimate plus 10-day 95% rh	2,325
8	Prestress to 80% ultimate plus 10-day 95% rh	2,230

* 4-inch-diameter chamber

*Table 8.8 Effect of Humidity on Hydroburst Pressures (30) **

	Balanced †		Weak ‡		Strong §	
Prestress Level, per cent	Control	Humidity Cycled (1)	Control	Humidity Cycled (1)	Control	Humidity Cycled (1)
	3,125	2,730	2,710	2,325	3,210	3,200
0	3,310	2,910	2,650	2,350	3,100	3,000
	3,250		2,650	2,300		2,625
40	3,300		2,750	2,200		2,300
	3,150	2,510	2,710	2,180	3,125	2,400
	2,800	2,620	2,650	2,225	3,125	2,725
80		2,780				
		2,700				
		2,800				

* 4-inch-diameter prestressed chambers made of 20 end roving preimpregnated.

† 4 hoop layers

‡ 3 hoop layers

§ 5 hoop layers

(1) per MIL-E-5272C

(*a*) *NOL rings.* The most universal composite considered for quality control testing of filament-wound structures is the NOL ring test. The NOL ring (most laboratories now utilize a ring 0.060 inch thick as a standard reference) is tested in the tensile test machine, and filament stress and composite stress at rupture are usually calculated. The resulting data may then be utilized as criteria of quality, either for a reinforcement or for the resin system employed.

In actuality, the NOL ring evaluates the tensile strength of the reinforcement. But because of a bending stress involved, the values reported are particularly dependent on the thickness of the ring. However, wide variations are often reported in stress levels even when there is a uniform geometry of test specimens and like materials of construction are used. NOL rings are more sensitive to processing variables than to materials of construction and, for this reason, should not be used to evaluate prepreg roving or resin matrices for quality control for a given type of filament. The NOL ring can and does distinguish between different types of filaments.

Nevertheless, the NOL ring is an excellent means of determining processing parameters. These include the effect of roving tension on final resin content, the bath temperature on resin pickup, and the utilization of heat on the mandrel.

(*b*) *Horizontal shear test.* This is the most practical method for measuring bond by using the horizontal shear test. This test is responsive to changes in the cure cycle which affect the cross-linking density of the resin and also for modifications of resin formulation which alter the shear characteristics and the finish of the glass.

In the test, a short segment of the NOL ring is used as the specimen, and this segment is centerloaded with the ends left free to spread as shown in the previous section on basic tests. Failure in shear occurs through the resin, at or very near the glass interface.

This test is employed as a means of quality control at room temperature, 250°F and after a 6-hour water boil. It should be noted that the NOL ring test places essentially no load on the resin or on the resin-to-glass interface.

(*c*) *Reliability tests.* Efforts are currently being made to standardize test techniques for detecting nonuniformity of glass filaments, resin anomalies, voids or inclusions, and delamination within the chamber wall. The relation of these shortcomings to the composite structure is indicated by controlled nondestructive tests.

Refer nces

1. Symposium on Standards for Filament-Wound Reinforced Plastics, ASTM Special Technical Publication No. 327, March 1963.
2. N. Fried, N.Y. Naval Applied Sciences Lab. Report 2, and 3, Project 6189, 1962.
3. Defense Specifications and Standards Reinforced Plastics, PLASTEC Note 3, Picatinny Arsenal, March 1963.
4. J. R. Barber, Mechanical Properties of a Filament Wound Laminate, Brunswick-Balke-Collender Test Report No. 1001 (September 1960).
5. Military Handbook MIL-HDBK-17, Part 1, "Reinforced Plastics," Armed Forces Supply Support Center, Washington, D.C., November 1959.
6. H. A. Perry, SAMPE *Meeting Report*, p. 162, March 1961.
7. F. R. Pflederer and T. G. Roskos, SPI Annual Preprint, Section 9-D, February 1963.
8. N. Fried, N.Y. Naval Applied Sciences Laboratory Progress Rep. 4, Project 6189 (for deep submergence) (7 January 1963).
9. F. R. Pflederer, SPI Annual Preprint, Section 1-D, February 1962.
10. F. R. Pflederer and S. S. Chen, "Critical Collapse of Thin Wall Reinforced Plastic Cylinders," A. O. Smith Corporation Report, 1963.
11. V. C. Cutler, SPI *Annual Report*, "Bending Analysis—Plastic Pipe," February 1961.
12. S. Timoshenko, *Strength of Materials*, Part II, D. Van Nostrand Co., New York, 1941.
13. F. Wolffand T. Siuta, *ARS Journal*, **32**, 948, June 1962.
14. K. A. Erwin, *SPE Journal*, **18**, 8 (August 1962).
15. F. J. McGarry and W. H. Haslett, *Modern Plastics*, **135**, December 1962 (Contract AF 33-(616)-6280 WADD).
16. MIT-MCA Plastics Research Project, Progress Report, January 15, 1959 (Resin Shrinkage).
17. H. T. Jessop, "Tardy and Senarmont Method of Measuring Fractional Relative Retardation," *Brit. J. Applied Physics*, **4**, 138 (1953).
18. N. A. Leeds, ASTM—NOL Symposium, "Developing standards for use of pre-impregnated roving," 6–7 June 1962.
19. R. W. Eshbaugh, SPI Preprint, Section 1A, February 1963.
20. H. A. Perry, SPI Preprint, Section GE, February 1962.
21. S. Timoshenko, Theory of Plates and Shells, D. Van Nostrand Co., New York, 1940.
22. I. M. Daniel, Armour Research Foundation Report 8194-3, p. 12 (15 May 1960).
23. Naval Ordnance Laboratory Report, Photoelastic Studies in Filament Wound Structures 1962–1963.
24. N. Fried, Naval Applied Sciences Laboratory, Survey of Methods of test for parallel filament reinforced plastics, June 1962.
25. R. J. Roark, *Formulas for Stress and Strain*, McGraw-Hill Book Co., New York (1954).
26. Proposed Military Specification MIL-P-27327, Plastic Material, Glass Fiber Base, Filament Winding.

27. B. C. Madden, Jr., Method of testing thin sheet material in compression, AAF Tech. Rep. 5311, 22 October 1945.
28. R. J. McBride, WADC TR 59-604 (February 1960).
29. Allison Division of General Motors Corporation, P. F. Duvall report on Quality Control Procedures for Rocket Motor Cases Reinforced Plastics versus Steel (1963).
30. P. N. Skinner and S. Brelant, *Plastics Technology*, **9**, 7, pp. 36–39 (July 1963).

appendix A Companies with filament winding facilities or capabilities

Aerojet-General Corp., 6352 N. Irwindale, Azusa, California
Aerojet-General Corp., Box 1947, Sacramento, California
Amercoat Corp., 4809 Firestone Blvd., Los Angeles, California
A. O. Smith Corp., 3533 N. 27th St., Milwaukee 1, Wisconsin
Apex Reinforced Plastics Div., White Sewing Machine Corp., Washington and Elm Sts., Cleveland, Ohio
Apollo-Carlon Co., Ponca City, Oklahoma
Atlas Plastics, Inc., 681 Seneca St., Buffalo 10, New York
B. F. Goodrich Rubber Co., 500 S. Main St., Akron, Ohio
Bendix Corp., 401 Bendix Dr., South Bend 20, Indiana
Black-Sivalls & Bryson, Inc., P.O. Box 749, Ardmore, Oklahoma
Boeing Aircraft Co., Box 3707, Seattle 24, Washington
Brunswick Corp., Marion, Virginia, & 4300 INDUSTRIAL AVE., LINCOLN, NEBRASKA
Brunswick Corp., 1700 Messler St., Muskegon, Michigan
Chrysler Corp., Missile Div., Attn: H. W. Haugen, 16 Mile Rd. at Von Dyke, Detroit, Michigan
Continental-Diamond Fibre Corp., Newark, Delaware
Columbia Products Co., RFD No. 3, Columbia, S. Carolina
Creative Engineering, 1769 Placentia, Costa Mesa, California
Douglas Aircraft Corp., 3000 Ocean Park Blvd., Santa Monica, California
Dow-Smith Corp., P.O. Box 584, Milwaukee, Wisconsin

Dynetics, Inc., Mountain Lakes, New Jersey
Food Machinery, 1105 Coleman Ave., San Jose, California
Formica Corp., 4614 Spring Grove Ave., Cincinnati, Ohio
Garlock Packing Co., Palmyra, New York
General Motors Corp., Allison Div., Indianapolis, Indiana
Goodyear Aerospace Corp., Akron, Ohio
Grumman Aircraft Corp., Bethpage, New York
Haveg Industries, Inc., Wilmington 8, Delaware
Hercules Powder Co., Young Development Lab., Rocky Hill, New Jersey
Hercules Powder Co., Salt Lake City, Utah
Hercules Powder Co., Wilmington, Delaware
H. I. Thompson Co., 1600 W. 135 St., Gardena, California
Hughes Aircraft Co., Culver City, California
Ingersoll Kalamazoo Div., Borg Warner Corp., Kalamazoo, Michigan
Justin Enterprises, Inc., Cincinnati, Ohio
Lamtex Industries, Motor Ave., Farmingdale, New York
Lockheed Aircraft Corp., 2555 N. Hollywood Way, Burbank, California
Lockheed Aircraft Corp., P.O. Box 504, Sunnyvale, California
Lockheed Aircraft Corp., 7701 Woodley Ave., Van Nuys, California
Lunn Laminates Inc., Straight Path, Wyandanch, New York
Narmco Research and Development, Div. of Telecomputing Corp., 3540 Aero Court, San Diego 23, California
National Fibre Co., Wilmington 99, Delaware
Olin-Mathieson Chemical Corp., 275 Winchester Ave., New Haven, Connecticut
Riverside Plastics Co., 220 Miller Rd., Hicksville, New York
Rocketdyne Div., North American Aviation, 6633 Canoga Ave., Canoga Park, California
Rohr Aircraft Co., Riverside, California
Schwader Bros. Div., Samsonite Luggage Co., Denver, Colorado
Spaulding Fibre Co., Inc., 310 Wheeler St., Tonawanda, New York
Structural Fibers, Inc., Fifth Ave., Chardon, Ohio
Structurlite Plastics Corp., Hebron, Ohio
Swedlow Plastics Co., 6986 Bandini Blvd., Los Angeles, California
Taylor Corp., Norristown, Pennsylvania
Thiokol Chemical Corp., Panelyte Industrial Div., Enterprise Ave., Trenton, New Jersey
Thiokol Chemical Corp., Brigham City, Utah
Thompson-Ramo-Wooldridge, Inc., 23555 Euclid Ave., Cleveland, Ohio

Universal Moulded Corp., Commonwealth Ave., Bristol, Virginia
U.S. Rubber Co., Mishawaka, Indiana
U.S. Rubber Co., Providence, Rhode Island
Vector Plastics Corp., 1275 Marconi Blvd., Copiague, New York
Walter Kidde Co., 675 Main St., Belleville, New Jersey

appendix B *Suppliers of reinforcements*

Code (A) Asbestos yarn, roving, fabric tape and/or felt tape
(G) Glass yarn, roving and/or fabric tape

Asbestos Corp., Quebec, Canada (A)
Asbestos Corp. of America, Garwood, New Jersey (A)
Bean Fiber Glass, Inc., Jaffrey, New Hampshire (G)
Clark-Schwebel Fiber Glass Corp., Livermore, California (G)
Dexter & Sons, Inc., Windsor Locks, Connecticut (A) (G)
DuPont de Nemours, E. I. & Co., Wilmington, Delaware (G)
Famco, Inc., Louisville, Kentucky (G)
Farrington Texol Corp., Walpole, Massachusetts (G)
Ferro Corp., Nashville, Tennessee (G)
Fiber Glass Industries, Inc., Amsterdam, New York (G)
Flightex Fabrics, Inc., New York, New York (G)
Gustin-Bacon Mfgr. Co., Kansas City, Missouri (G)
Haveg Industries, Inc., Wilmington, Delaware (A) (G)
Hess, Goldsmith & Co., New York, New York (G)
Johns-Manville Corp., New York, New York (A) (G)
Minnesota Mining & Mfgr. Co., St. Paul, Minnesota (G)
Modiglass Fibers, Inc., Bremen, Ohio (A) (G)
North American Asbestos Corp., Chicago, Illinois (A)
Owens-Corning Fiberglas Corp., New York, New York (G)
Pittsburgh Plate Glass Co., Pittsburgh, Pennsylvania (G)
Raybestos-Manhattan, Inc., Manheim, Pennsylvania (A) (G)

Rogers Corp., Rogers, Connecticut (A) (G)
Stevens, J. P., Co., New York, New York (A) (G)
Thompson, H. I., Fiber Glass Co., Gardena, California (G)
U.S. Rubber Co., New York, New York (A) (G)
Western Backing Corp., Culver City, California (A) (G)

appendix C *Suppliers of resins*

Code (A) Alkyds
(E) Epoxy
(Ph) Phenolics
(Po) Polyester

Allied Chemical Corp., New York, New York (A) (E) (Ph) (Po)
American Cyanamid Co., Wallingford, Connecticut (Po)
Archer-Daniels-Midland Co., Minneapolis, Minnesota (A) (E) (Po)
Armstrong Products Co., Warsaw, Indiana (E)
Atlas Chemical Industries, Inc., Wilmington, Delaware (Po)
Atlas Mineral Products Co., Mertztown, Pennsylvania (E) (Ph) (Po)
Bacon Industries, Inc., Watertown, Massachusetts (Ep)
Badische Anilin & Soda-Fabrik, A.G., Ludwigshafen/Rhein, Germany (Ep) (Ph) (Po)
Borden Chemical Co., New York, New York (Ep) (Ph)
Bradley & Vrooman Co., Chicago, Illinois (A) (Ep) (Ph)
Cabot Corp., Philadelphia, Pennsylvania (Po)
Cadillac Plastic & Chemical Co., Detroit, Michigan (E) (Po)
Catalin Corp. of America, New York, New York (Ph)
Celanese Corp. of America, Newark, New Jersey (Po)
Chemical Coatings & Engineering Co., Media, Pennsylvania (A) (E) (Po)
Chemische Werke Huls, A.G., Marl, Germany (Po)
Ciba Corp., Fair Lawn, New Jersey (E)

Conap, Inc., Allegany, New York (E)
Cook Paint & Varnish Co., No. Kansas City, Missouri (A) (E) (Ph) (Po)
Diamond Alkali Co., Cleveland, Ohio (Po)
Dow Chemical Co., Midland, Michigan (E) (Ph)
Durez Plastics/Hooker Chemical Corp., No. Tonawanda, New York (Ph) (Po)
Eastman Chemical Products, Inc., Kingsport, Tennessee (Po)
Emerson and Cuming, Inc., Canton, Massachusetts (E)
FMC Corp., New York, New York (E)
Furane Plastics, Inc., Los Angeles, California (E)
General Electric Co., Pittsfield, Massachusetts (Ph)
General Mills, Inc., Kankakee, Illinois (E)
Glidden Co., Cleveland, Ohio (Po)
Hastings Plastics, Inc., Santa Monica, California (E) (Ph)
Hercules Powder Co., Wilmington, Delaware (A)
Hysol Corp., Olean, New York (E)
Imperial Chemical Industries, Ltd., London, England (A) (Ph) (Po)
Interchemical Corp., Newark, New Jersey (Po)
Jones-Dabney Co., Devoe and Raynolds, Co., Louisville, Kentucky (E)
Koppers Co., Pittsburgh, Pennsylvania (E) (Ph)
Marblette Corp., Long Island City, New York (E) (Ph)
Marco Chemical, Newark, New Jersey (A)
Metachem Resins Corp., Cranston, Rhode Island (E) (Po)
Minnesota Mining & Mfgr. Co., St. Paul, Minnesota (E) (Ph)
Mol-Rez, Div. of American Petrochemical Corp., Minneapolis, Minnesota (A)
Monsanto Chemical Co., St. Louis, Missouri (A) (E) (Ph) (Po)
Montecatini, Milan, Italy (Ph) (Po)
Narmco Materials Div. TC, Costa Mesa, California (E) (Ph)
Raybestos-Manhattan, Inc., Bridgeport, Connecticut (E) (Ph)
Reichhold Chemicals, Inc., White Plains, New York (A) (E) (Ph) (Po)
Rohm & Haas Co., Philadelphia, Pennsylvania (A) (Ph) (Po)
Shell Chemical Co., New York, New York (E)
Synvar Corp., Wilmington, Delaware (A)
Union Carbide Corp., New York, New York (E) (Ph)
U.S. Rubber Co., Naugatuck Chemical Div., Naugatuck, Connecticut (Po)

appendix D Suppliers of preimpregnated reinforcements

Black River Pool & Plastics, Inc., Peapack, New Jersey
Chicago Printed String Co., 2320 W. Logan Blvd., Chicago, Illinois
Coast Mfgr. & Supply Co., Livermore, California
Cordo Chemical Corp., 230 Park Ave., New York, New York (and Mobile, Alabama)
Duracote Corp., 350 N. Diamond St., Ravena, Ohio
Fabricon Products Div., Eagle Pitcher Co., 1900 W. Pleasant Ave., River Rouge, Michigan
Fiberfil, Inc., Fox Farm Rd., Warsaw, Indiana
Minnesota Mining & Mfgr. Corp., 900 Bush Ave., St. Paul, Minnesota
Narmco Materials Div., Telecomputing Corp., 600 Victoria St., Costa Mesa, California
National Coating Co., West Hanover, Massachusetts
Raybestos-Manhattan, Inc., Manheim, Pennsylvania
Sandman Co., P.O. Box 801, Worcester, Massachusetts
Spaulding Fibre Co., Inc., 310 Wheeler St., Tonawanda, New York
Standard Insulation Co., Inc., 74 Paterson Ave., East Rutherford, New Jersey
Taylor Corp., Norristown, Pennsylvania
U.S. Polymer Chemicals Co., 700 E. Dyer Rd., Santa Ana, California (and Stamford, Connecticut)
Woodall Industries, Inc., 7565 E. McNichols Rd., Detroit, Michigan

appendix E Glossary

A-Stage. An early stage in the reaction of a thermosetting resin in which the material is still soluble in certain liquids and fusible. *See also* B- and C-stages.

Accelerator. An agent used to hasten a reaction to reduce the time required for a thermosetting resin to cure or harden.

Acrylic ester. An ester of acrylic acid, or of a structural derivative of acrylic acid, for example, methyl methacrylate.

Acrylic resin. A synthetic resin prepared from acrylic acid or from a derivative of acrylic acid.

Addition polymerization. *See* Polymerization.

Adhesion. The state in which two surfaces are held together by interfacial forces, which may consist of valence forces or interlocking action or both.

Adhesive. A substance capable of holding materials together by surface attachment. Adhesive is the general term and includes, among others, the synthetic resin adhesives as well as the vegetable and animal base adhesives, such as cements, glues, mucilages, and pastes. These terms are sometimes used loosely and interchangeably.

Adsorption. The adhesion of the molecules of gases, dissolved substances, or liquids in more or less concentrated form to the surfaces of solids or liquids with which they are in contact.

After-bake. *See* Post-cure.

Aging. The change in properties of a material with time under stated conditions.

Alkyd resin. Polyester resins made with some fatty acid as a modifier. *See* Polyester.

Alloy. Composite material made up by blending polymers or copolymers with other polymers or elastomers under selected conditions, for example, styrene-acrylonitrile copolymer resins blended with butadiene-acrylonitrile rubbers.

Allyl resin. A synthetic resin formed by the polymerization of chemical compounds containing the group $CH_2{=}CH{-}CH_2{-}$. The principal commercial allyl resin is a casting material that yields allyl carbonate polymer.

Annealing. A process of holding a material at a temperature near, but below, its melting point, the objective being to permit stress relaxation without distortion of shape. It is often used on molded articles to relieve stresses set up by flow into the mold.

Anti-oxidant. Substance which prevents or slows down oxidation of material exposed to air.

APU. Auxiliary power unit.

Asbestic. Word used to describe certain short types of asbestos.

Asbestos. It is not the name of a distinct mineral species but is a commercial term applied to fibrous varieties of several minerals.

Attenuation. The process of making thin or slender. It applies to the formation of fiber from molten glass.

Autoclave. (1) Closed strong vessel for conducting chemical reactions under high pressure. (2) In low-pressure laminating, a round or cylindrical container in which heat and gas pressure can be applied to the resin-impregnated paper or fabric positioned in layers over a mold.

B-Stage. An intermediate stage in the reaction of a thermosetting resin in which the material softens when heated and swells in contact with certain liquids but does not entirely fuse or dissolve. Resins in thermosetting molding compounds are usually in this stage. *See also* A-Stage and C-Stage.

Back pressure. Resistance of a material, because of its viscosity, to continued flow when mold is closing.

Bag molding. A method of applying pressure during bonding or molding, in which a flexible cover, usually in connection with a rigid die or mold, exerts pressure on the material being molded, through the application of air pressure or drawing of a vacuum.

Ball mill. A cylindrical mill containing steel, porcelain, or flint balls within the revolving cylinder which supply the grinding action and reduce the size of the particles present in the material being milled.

Banbury. An apparatus for compounding materials composed of a pair of contra-rotating, rotors which masticate the materials to form a homogeneous blend.

Bare glass. Bare glass is the product in fiber form before binder, size, or other coating is applied. It also describes glass fibers from which the size or other coating has been removed by burning off during test to measure ignition loss.

Binder. A formulated preparation applied to fibers to increase integrity of the product to desired degree and to hold fibers in position in a mat structure.

Bleed. To give up color when in contact with water or a solvent; undesired movement of certain materials in a plastic (for example, plasticizers in vinyl) to the surface of the finished article or into an adjacent material. Also called Migration.

Blister. A raised area on the surface of a molding caused by the pressure of gases inside it on its incompletely hardened surface.

Blocking. An undesired adhesion between touching layers of a material, such as occurs under moderate pressure during storage or use.

Body. (n.) A qualitative indication of the viscosity of oil, varnish, or paint; "heavy body" denotes a relatively high viscosity and "light body" a relatively low viscosity. (v.) To increase the viscosity of an oil by heat treatment or by other means.

Boss. Protuberance on a plastic part designed to add strength, to facilitate alignment during assembly, to provide for fastenings, etc.

Branched. In molecular structure of polymers (as opposed to Linear), refers to side chains attached to the main chain. Side chains may be long or short.

Breathing. The opening and closing of a mold to allow gases to escape early in the molding cycle. Also called degassing. When referring to plastic sheeting, "breathing" indicates permeability to air.

Bulk factor. Ratio of the volume of material before molding or fabricating to volume after molding or fabricating.

Bursting strength. A measure of ability of a material to withstand hydrostatic pressure without rupture. It is calculated by dividing maximum net pressure observed by the cross-sectional area of the exposed diaphragm portion of the specimen.

Bushing. The unit through which molten glass is drawn in making glass fibers.

C-Stage. The final stage in the reactions of a thermosetting resin in which the material is relatively insoluble and infusible. Thermosetting resins in a fully cured plastic are in this stage. *See* A-Stage and B-Stage.

Calender. To prepare sheets of material by pressure between two or more revolving rollers. Used in connection with preparation of films and coating of materials.

Card. A machine consisting of rolls, the surfaces of which are covered (brush-like) with many projecting wires which clean and separate the fibers and convert them into slivers; used, generally, in the cotton, woolen and asbestos industries.

Catalyst. A substance which markedly speeds up the cure of a compound when added in minor quantity as compared to the amounts of primary reactants. *See* Hardener, Inhibitor, Promoter.

Catenary. A measure of the difference in length of the strands as a result of unequal tension.

Cavity. Depression in a mold made by casting, machining, hobbing, or a combination of these methods; depending on number of such depressions, molds are designated as single-cavity or multi-cavity.

Chamber pressure. The pressure of gases within a firing chamber.

Charge. The measurement or weight of material, either liquid, preformed, or powder, used to load a mold.

Coefficient of expansion. The fractional change in length (sometimes volume, specified) of a material for a unit change in temperature.

Cold flow. The distortion which takes place in materials under load at room temperature. *See* Creep.

Cold molding. A procedure in which a composition is shaped at room temperature and cured by subsequent baking.

Compression mold. A mold which is open when the material is introduced and which shapes the material by heat and by the pressure of closing.

Compressive strength. Crushing load at the failure of a specimen divided by the original sectional area of the specimen.

Composite. A composite can be (1) a combination of two or more materials either of which could have useful structural properties by itself, (2) composed of dissimilar materials bonded together so that it acts as homogeneous or coordinating single structure, and/or (3) a combination of strong fibers in

a matrix of lower strength. The latter description depicts most composites such as filament-wound types.

C ndensation. A chemical reaction in which two or more molecules combine with the separation of water or some other simple substance. If a polymer is formed, the condensation process is called polycondensation. *See also* Polymerization.

Condensation resin. A resin formed by polycondensation, for example, the alkyd, phenol-aldehyde, and urea formaldehyde resins.

Cone. In textiles, a package of yarn wound in transverse form on a conical shaped tube or bobbin, the yarn of which is unwound from the small end of the package; used in knitting, high-speed wrapping, filament winding, etc.

Contact pressure resins. Liquid resins which thicken or resinify on heating and, when used for bonding laminates, require little or no pressure.

Continuous filament. An individual rod of glass of small diameter with flexibility and great or indefinite length.

Copolymer. *See* Polymer.

Core. (1) The central member of a sandwich construction (can be honeycomb material, foamed plastic, or solid sheet) to which the faces of the sandwich are attached; the central member of a plywood assembly. (2) A channel in a mold for circulation of heat-transfer media. (3) Part of a complex mold that molds undercut parts. Cores are usually withdrawn to one side before the main sections of the mold open. Also called core pin.

Count. The number of warp yarn (ends) and filling yarns (picks) per inch.

Count of cloth. The texture of a fabric or ends and picks per inch designated, for example, as 60 x 56, or 60 ends of warp x 56 picks of filling.

Crazing. Fine cracks which may extend in a network on or under the surface or through a layer of a plastic material.

Creel. A stand or frame for holding the required number of roving balls or supply packages in desired position for unwinding onto the next processing step.

Creep. The dimensional change with time of a material under load.

Cross-laminated. Laminated so that some of the layers of material are oriented at right angles to the remaining layers with respect to the grain or strongest direction in tension. Normally balanced construction of the laminations about the center line of the thickness of the laminate is assumed. *See* Parallel-laminated.

Cryogenic fuel. A rocket fuel that either in itself is kept at very low temperatures or combines with an oxidizer kept at very low temperatures.

Cryogenics. The science of low-temperature conditions.

Cure. To change the physical properties of a material by chemical reaction, which may be condensation, polymerization, or vulcanization; usually accomplished by the action of heat and catalysts, alone or in combination, with or without pressure.

Daylight opening. Clearance between two platens of a press in the open position.

Deformation under load. The dimensional change of a material under load for a specified time following the instantaneous elastic deformation caused by the initial application of the load. Sometimes referred to as cold flow or creep.

Delaminati n. The separation of a laminate into layers owing to failure of adhesion of the binder or failure of cohesion of the filler.

Denier. The weight, in grams, of 9,000 meters of yarn is the denier. The lower the denier, the finer the yarn.

D nsity. Weight per unit volume of a substance, expressed in grams per cubic centimeter, pounds per cubic foot, etc.

Desizing. The process of eliminating sizing, which is generally starch, from gray goods prior to applying special finishes or bleaches for yarn such as glass or cotton.

Devitrification. Crystallization in glass.

Dielectric. Insulating material. In radio-frequency preheating, dielectric may refer specifically to the material which is being heated.

Dielectric heating (electronic heating). The plastic to be heated forms the dielectric of a condenser to which is applied a high-frequency (20-to-80-mc) voltage. Dielectric loss in the material is the basis. Process used for sealing vinyl films and preheating thermoset molding compounds.

Dimensional stability. Ability of a plastic part to retain the precise shape in which it was molded, fabricated, or cast.

Dip coating. Applying a plastic coating by dipping the article to be coated into a tank of melted resin or plastisol, then chilling the adhering melt.

Doctor roll or bar. A device for regulating the amount of liquid adhesive or resin on the rollers of a spreader or impregnator.

Doff. The act of removing a full package such as a roving ball from a winding machine.

Draft. The degree of taper of a side wall or the angle of clearance designed to facilitate removal of parts from a mold.

Dry winding. A term used to describe filament winding using preimpregnated roving as differentiated from wet winding where unimpregnated roving is pulled through a resin bath just prior to winding on mandrel. *See* Wet winding.

Dyne. Unit of force that will accelerate a particle having a mass of 1 gram per 1 centimeter per second.

E-Glass. *See* Glass, types of.

Elastomer. A material which at room temperature stretches under low stress to at least twice its length and snaps back to the original length on release of stress.

Elongation. The fractional increase in length of a material stressed in tension.

Emissivity. The ratio of the total heat-radiating power of a surface to that of a black body of the same area and at the same temperature.

Encapsulating. Enclosing an article in a closed envelope of plastic by immersing the object in a casting resin.

End. An individual sliver, roving, yarn or cord. In a fabric, an end is a warp yarn (running the length of the fabric).

End count. An exact number of ends supplied on a ball or roving.

Endothermic reaction. A reaction that absorbs heat.

Epoxy resins. Based on ethylene oxide, its derivatives or homologs, epoxy resins form straight-chain thermoplastics and thermosetting resins, for example, by the condensation of bisphenol and epichlorohydrin.

Ester. The reaction product of an alcohol and an acid.

Exothermic reaction. A reaction that liberates heat.

The compacting of extrusion. The compacting of a plastic material and the forcing of it through an orifice in more or less continuous fashion.

Extender. A substance, generally having some adhesive action, added to a plastic composition to reduce the amount of the primary resin required per unit area.

Fabric. Any woven, knitted, felted, bonded, or knotted textile material. Note that there are woven fabrics and nonwoven fabrics. The nonwovens are represented by papers, felts, etc.

Fabricate. To work a material into a finished form by machining, curing, forming, or other operation.

Felt. A fibrous material made up of interlocked fibers by mechanical or chemical action, moisture or heat. Felts can be made of many different fibers, including asbestos, cotton, glass, etc. *See* Fabrics.

Fiber. This term usually refers to relatively short lengths of very small cross sections of various materials. Fibers can be made by chopping filaments (converting). Staple fibers may be ½ to a few inches in length and usually 1 to 5 denier.

Filament. A single, thread-like fiber or a number of these fibers put together. A variety of fiber characterized by extreme length, which permits its use in yarn with little or no twist and usually without the spinning operation required for fibers.

Filament winding. Basically produces high-strength and lightweight products; consists basically of two ingredients; namely, a filament or tape type reinforcement and a matrix or resin.

Filler. A low-cost, inert substance added to a plastic to make it less costly. Fillers may also improve physical properties, particularly hardness, stiffness, and impact strength. The particles are usually small, in contrast to those of reinforcements, but there is some overlap between the functions of the two.

Fillet. A rounded filling of the internal angle between two surfaces of a plastic molding.

Film. An optional term for sheeting having a nominal thickness not greater than 0.010 inch.

Finish. A material applied to the surface of glass fibers or other fibers used to reinforce plastics and intended to improve the physical properties of such reinforced plastics over that obtained using glass reinforcement without finish.

Firing chamber. Chamber in rocket engine in which the fuel and oxidizer are ignited and in which pressure of gases is built up to provide an exhaust velocity sufficient to attain thrust.

Flash. The excess molding material which runs out of the cut-off when a mold is closed.

Flash mold. A mold designed to permit escape of excess molding material. Such a molding material relies upon back-pressure to seal the mold and put the piece under pressure.

Float. A warp or filling thread that lies on top of the opposite series of yarn for a distance of several threads.

Flow. (1) The movement of resin under pressure, allowing it to fill all parts of a mold. (2) Flow or "creep": The gradual but continuous distortion of a material under continued load, usually at high temperatures.

Foam d plastics. (1) Resins in sponge form. The sponge may be flexible or rigid, the cells closed or interconnected, the density anything from that of the solid parent resin down to, in some cases, 2 pounds per cubic foot. (2) Compressive

strength of rigid foams, making them useful as core materials for sandwich structures. Both types are good heat barriers.

Forming package. A single glass strand gathered on a thin-wall paper or plastic tube. The initial step in the process of manufacturing.

Frit. Basic ingredient of porcelain enamels. Consists primarily of inorganic oxides, minerals, fluorides, or salts.

Furan resins. Dark-colored, thermosetting resins available primarily as liquids ranging from low-viscosity polymers to thick, heavy sirups.

Fuzz. A measure of broken filaments in a strand or roving.

G or G-Force. The measure of the gravitational pull of the earth as modified by the earth's rotation, equal to the acceleration of a freely moving body at the rate of 32.16 feet/second/second.

Gel. (1) The name given to any gelatinous mass. (2) The "stage" at which a polymerizing resin composition thickens to a semisold state.

Gelation. The formation of a gel.

Gigg. A machine for raising a nap on fabrics.

Glass, types of. Includes E—electrical grade, S—high-strength, D—low-dielectric.

Grain. In textiles, a measure of weight used in woolen yarn calculations, the basis of grain weighing being 20 yards of yarn; one grain yarn would be equal to 140,000 yards per pound, etc.

Gray. Any fabric before finishing, as well as any yarn or fiber before bleaching or dyeing.

Greige. A silk or synthetic filament term for gray.

Grex. A universal yarn numbering system in which the yarn number is equal numerically to the weight in grams per 10,000 meters.

Guide eye. An eye (platinum, ceramic, etc.) through which a sliver, fiber, strand, etc., passes when directed from creel to mandrel.

Hardener. A substance or mixture of substances added to plastic composition, or an adhesive to promote or control the curing reaction by taking part in it. The term is also used to designate a substance added to control the degree of hardness of the cured film. *See also* Catalyst.

Heat cleaning. The process whereby the organic size or treatment on the glass surface is removed by application of heat. It is used primarily on woven fabric where an alternate finish is desired.

Heat-convertible resin. A thermosetting resin convertible by heat to an infusible and insoluble mass.

Heat-distortion point. The temperature at which a standard test bar (ASTM D 648) deflects 0.010 inch under a stated load of either 66 or 264 psi.

High-pressure laminates. Laminates molded and cured at pressures not lower than 1,000 psi.

Honeycomb. Manufactured product consisting of sheet-metal or a resin-impregnated sheet material (paper, fibrous glass, etc.) which has been formed into hexagonal-shaped cells. Used as core material for sandwich constructions.

Hoop stress. The circumferential stress in a material of cylindrical form subjected to internal or external pressure produces hoop stress.

HTS. A size applied to the glass fiber surface during forming of the fibers to give high performance compatibility with resin and resistance to mechanical damage to the individual filaments, strands, or ends. (Trade Mark of Owens-Corning Fiberglas Corporation.)

Hydrophilic. Capable f adsorbing or absorbing water.

Hydrophobic. Capable of repelling water.

Ignition loss. The difference in weight before and after burning off the binder or size to determine the binder or size weight (ignition loss). Usually expressed as a per cent of the original weight of the sample.

Inert. Not chemically reactive.

Infusible. Not melting under heat.

Inhibitor. A substance that slows down chemical reaction. Inhibitors are sometimes used in certain types of monomers and resins to prolong storage life.

Insert. An integral part of a plastics molding consisting of metal or other material which may be molded into position or pressed into the molding after the molding is completed.

Jacket. An enveloping hollow metal cover for holding circulating steam or water used to heat or cool the mechanism it covers (such as a mixing vessel, mold, or platen).

Kelvin scale. A temperature scale that uses Centigrade degrees but makes the zero degree signify absolute zero (or minus 273.18°C).

Laminated plastics. A plastics material consisting of superimposed layers of a synthetic resin-impregnated or -coated filler which have been bonded together, usually by means of heat and pressure, to form a single piece such as filament-wound units.

Land. The portion of a mold which provides the separation or cutoff of the flash from the molded piece. The horizontal bearing surface of a semipositive or flash mold.

Lap. A matted sheet of cotton wound on a spindle, produced by the picker. Cotton lap is used extensively in preparing asbestos-cotton mixes in the carding machine.

Lay. The spacing of the roving bands on the roving package expressed in the number of bands per inch.

Lay-up. The arrangement of reinforcing material and the resin in its uncured state.

Loops and snarls. Small open places in the strands owing to the excessive length of one or more strands, which is the result of unevenly distributed tension allowing certain strands or filaments to slip while others are completely controlled.

Lot. A specific amount of glass roving produced at one time and offered for sale as a unit quantity.

Low-pressure laminates. In general, laminates molded and cured in the range of pressures from 400 psi down to and including pressures obtained by the mere contact of the plies.

Mandrel. The core around which paper, fabric, or resin-impregnated fibrous glass is wound to form pipes, tubes, vessels, etc.

Marble. Small spheres of glass used for melting and subsequent drawing into glass fibers.

Mat. A randomly distributed felt of glass fibers used in reinforced plastics lay-up molding.

Matched-metal molding. Method of molding reinforced plastics between two close-fitting metal molds mounted in a hydraulic press.

Micron. One micron = .001 millimeter = .00003937 inches.

Mil. The unit used in measuring the diameter of glass strands, wire, etc. (one mil = .001 inch).

M dulus f elasticity. The ratio of stress to strain in a material that is elastically deformed.

Mold. (v.) To shape plastic parts or finished articles by heat and pressure. (n.) (1) The cavity or matrix into which the plastic composition is placed and from which it takes its form; (2) The assembly of all the parts that function collectively in the molding process.

Molding. Sometimes used to denote finished piece.

Molding cycle. (1) The period of time occupied by the complete sequence of operations on a molding press requisite for the production of one set of moldings. (2) The operations necessary to produce a set of moldings without reference to the time taken.

Molding shrinkage. The difference in dimensions, expressed in inches per inch, between a molding and the mold cavity in which it was molded, both the mold and the molding being at normal room temperature when measured.

Mold release. *See* Parting agent.

Monofilament (monofil). A single filament of indefinite length. Monofilaments are generally produced by extrusion.

Monomer. A relatively simple compound which can react to form a polymer.

Multifilament yarn. A multitude of fine continuous filaments, often 5 to 100 individual filaments, usually with some twist in the yarn to facilitate handling. Multifilament yarn sizes are described in denier and range from 5 to 10 denier up to a few hundred denier. The larger deniers, even in the thousands, are usually obtained by plying smaller yarns together. Individual filaments in a multifilament yarn are usually about 1 to 5 denier.

MVT (moisture vapor transmission). A rate at which water vapor will penetrate a film of material over a given time at a specified temperature and relative humidity (grams-mil/24 hours-100 inch).

Nonwoven. *See* Fabric.

Novolac. A phenolic-aldehyde resin which, unless a source of methylene groups is added, remains permanently thermoplastic. *See also* Thermoplastic.

Orifice. The hole in the bushing tip from which flows the stream that is drawn out into a glass fiber or filament.

Paper. A thin fibrous sheet material produced from cotton, wood pulp, asbestos, etc., using the established paper-making processes (wet or dry).

Parallel-laminated. Laminated so that all the layers of material are oriented approximately parallel with respect to the grain or strongest direction in tension. *See also* Cross-laminated.

Parting agent. A lubricant, often wax, used to coat a mold cavity to prevent the molded piece from sticking to it, and thus to facilitate its removal from the mold.

Permeability. (1) The passage or diffusion of a gas, vapor, liquid, or solid through a barrier without physically or chemically affecting it. (2) The rate of such passage.

pH. The measure of the acidity or alkalinity of a substance, neutrality being at pH 7. Acid solutions are less than 7, alkaline solutions more than 7.

Phenolic resin. A synthetic resin produced by the condensation of an aromatic alcohol with an aldehyde, particularly of phenol with formaldehyde. Phenolic resins form the basis of thermosetting molding materials, laminated sheet, and stoving varnishes.

Pick. An individual filling yarn (running the width of a woven fabric at right angles to the warp). In England it is termed woof or weft.

Plastic. One of a large and varied group of materials which consists of, or contains as an essential ingredient, an organic substance of large molecular weight; and which, though solid in the finished state, at some stage in its manufacture has been or can be formed into various shapes by flow, usually through the application of heat and/or pressure.

Plasticizer. A chemical agent added to plastic compounds to make them softer and/or more flexible.

Platens. The mounting plates of a press, to which the entire mold assembly is bolted.

Ply. In general denotes fabrics or felts consisting of several layers (laminates, etc.). Also refers to yarn resulting from twisting operation.

Polyester. A resin formed by the reaction between a dibasic acid and a dihydroxy alcohol, both organic. Modification with multifunctional acids and/or bases and some unsaturated reactants permit cross-linking to thermosetting resins. Polyesters modified with fatty acids are called alkyds.

Polymer. A high-molecular-weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit, the mer; for example, polyethylene, rubber, cellulose. Synthetic polymers are formed by addition or condensation polymerization of monomers. If two or more nonomers are involved, a copolymer is obtained. Some polymers are elastomers, some plastics.

Polymerization. A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When two or more monomers are involved, the process is called copolymerization or heteropolymerization.

Positive mold. A mold designed to trap all the material when it closes.

Post-cure. In certain resins, complete cure and ultimate mechanical properties are attained only by exposure of the cured resin to higher temperatures than those of curing.

Postforming. The forming, bending, or shaping of fully cured, C-stage thermoset laminates that have been heated to make them flexible. On cooling, the formed laminate retains the contours and shape of the mold over which it has been formed.

Pot life. Life of a liquid resin from the time the catalyst has been added to the time when it is no longer usable because of gelatine or initial cure.

Potting. Similar to encapsulating, except that steps are taken to insure complete penetration of all the voids in the object before the resin polymerizes.

Precipitate. (n.) Material separated out of a solution in the form of a solid. (v.) Act of separating out such solid by either physical or chemical means.

Preform. (1) A preshaped fibrous reinforcement formed by distribution of chopped fibers by air, water flotation, or vacuum over the surface of a perforated screen to the approximate contour and thickness desired in the finished part. (2) A preshaped fibrous reinforcement of mat or cloth formed to desired shape on a mandrel or mock-up prior to being placed in mold press. (3) A compact pill formed by compressing premixed material to facilitate handling and control of uniformity of charges for mold leading.

Preheating. The heating of a compound prior to molding or casting in order to facilitate the operation or to reduce the molding cycle.

Preimpregnation. The practice of mixing resin and reinforcement before shipping it to the molder.

Premix. A molding compound prepared prior to and apart from molding operations and containing all components required for molding. These are resin, fibrous reinforcement in chopped form, fillers, catalysts, release agents, and other compounds.

Prepreg. Ready-to-mold material in web form which may be cloth, mat, or paper impregnated with resin and stored for use.

Promoter. A chemical, itself a feeble catalyst, that greatly increases the activity of a given catalyst.

Psi. Pounds per square inch.

Rankin scale. A temperature scale that uses Fahrenheit degrees but makes the zero degree signify absolute zero (or minus 459.72°F).

Release agent. *See* Parting agent.

Resin. Any of a class of solid or semisolid organic products of natural or synthetic origin, generally of high molecular weight having no definite melting point. Most resins are polymers.

Reinforcement. A strong inert material bound into a plastic to improve its strength, stiffness, and impact resistance. Reinforcements are usually long fibers of glass, asbestos, sisal cotton, etc., in woven or nonwoven form. To be effective, the reinforcing material must form a strong adhesive bond with the resin.

Reinforced molding compound. Compound supplied by raw material producer in the form of ready-to-use materials; as distinguished from premix.

Resin pocket. An apparent accumulation of excess resin in a small, localized section visible on cut edges of molded surfaces.

Ribbonization. Describes the degree of bonding together of the strands of roving which make up the roving band.

Rosin. A resin obtained as a residue in the distillation of crude turpentine from the sap of the pine tree (gum rosin) or from an extract of the stumps and other parts of the tree (wood rosin).

Roving (filament winding). The term roving is used to designate a collection of bundles of continuous filaments either as untwisted strands or as twisted yarns. Rovings may be lightly twisted, but for filament winding they are generally wound as bands or tapes with as little twist as possible. Glass rovings are predominantly used in filament winding.

Roving (textile). A form of fibrous glass having less twist than is present in a yarn. As a fibrous glass reinforcement, it means strands of continuous fibers wound into a cylindrical spool. Usually 60 strands, or ends are used. For staple fibers, roving is used to designate one or more slivers with a very small amount of twist and thus indicates an intermediate stage between sliver and yarn.

Roving band. A collection of strands or ends which act together as a band or ribbon.

Sandwich constructions. Panels composed of a lightweight core material—honeycomb, foamed plastic, etc.—to which two relatively thin, dense, high-strength faces or skins are adhered.

Saturated comp unds. Organic compounds which do not contain double or triple bonds and thus cannot add on elements or compounds.

Set. To convert a resin into a fixed or hardened state by chemical or physical action, such as condensation, polymerization, vulcanization, or gelation.

Shelf lif . Life of a resin when stored in its shipping container and without the addition of a catalyst. Life depends on exposure to sunlight, storage temperature, and humidity.

Sintering. In forming articles from fusible powders, for example, nylon, the process of holding the pressed-powder article at a temperature just below its melting point for about ½ hour. Particles are fused (sintered) together, but the mass as a whole does not melt.

Sisal. A white fiber produced from the leaves of the agave plant found in Central America, the West Indies, and Africa. Used primarily for cordage and binder twine.

Size. A variety of substances used in sizing fibers or fabrics, such as starch, chromium complex, etc. Different sizings are used for different applications. In reinforced plastics, sizings are added to promote bond between resins and fibers.

Sliver. A number of staple or continuous-filament fibers aligned in a continuous strand without twist. *See* Strand.

Slug. A particle of glass sometimes taking the form of a glass bead, which is imperfection in glass wool or textile fiber.

Solid propellant. Rocket propellant in solid state, composed of all the ingredients necessary for sustained chemical combustion, consisting of a compound of fuel and oxidizer, usually in plasticlike caked form. They burn on their exposed surface, generating hot exhaust gases to produce a reaction force.

Solvent. Dissolving liquid used to thin a resin (such as a phenolic resin) which may be too thick to use for impregnation. After the reinforcement material has been treated with the solvent and resin solution, the solvent is driven off by air drying or by heating. Solvents complicate processing. They may be recovered through condensation or sacrificed.

Specific gravity. The ratio of the weight of any volume of a substance to the weight of an equal volume of another substance taken as standard at a constant or stated temperature. Solids and liquids are usually compared with water at 4°C.

Specific heat. The quantity of heat required to raise the temperature of a unit mass 1 degree under specified conditions of pressure, etc.

Spinning. Process of making fibers by forcing plastic melt through spinneret.

Split-ring mold. A mold in which a split cavity block is assembled in a chase to permit the forming of undercuts in a molded piece. These parts are ejected from the mold and then separated from the piece.

Stabilizer. An ingredient used in the formulation of some plastics, especially elastomers, to assist in maintaining the physical and chemical properties of the compounded materials at their initial values throughout the processing and service life of the material.

Staple fibers. Fibers of spinnable length manufactured directly or by cutting continuous filaments to short lengths.

Storage life. The period of time during which a liquid resin or packaged adhesive can be stored under specified temperature conditions and remain suitable for use. Sometimes called shelf life.

Strain. The change per unit length in a linear dimension of a body.

Strands. A primary bundle of continuous filaments combined in a single compact unit without twist. These filaments (usually 51, 102, or 204) are gathered together in the forming operation. *See* Sliver.

Synthetic. Chemical compound made from elements or simple compounds; applied particularly to substances that duplicate other substances occurring in nature.

Synthetic resin. A complex, substantially amorphous, organic semisolid or solid material (usually a mixture) built up by chemical reaction of comparatively simple compounds, approximating the natural resins in luster, fracture, comparative brittleness, insolubility in water, fusibility or plasticity, and some degree of rubber-like extensibility; but commonly deviating widely from natural resins in chemical constitution and behavior with reagents.

Tack. Stickiness of an adhesive or filament reinforced resin prepreg material.

Tenacity. The term generally used in yarn manufacture and textile engineering to denote the strength of a yarn or of a filament for its given size. Numerically it is the grams of breaking force per denier unit of yarn or filament size; grams per denier, gpd. The yarn is usually pulled at the rate of 12 inches per minute. Tenacity equals breaking strength (grams) divided by denier. (Tenacity, gpd.)

Textile fibers. Fibers or filaments that can be processed into a yarn or made into a fabric by interlacing in a variety of methods, including weaving, knitting, and braiding.

Thermal conductivity. Ability of a material to conduct heat. The physical constant for quantity of heat that passes through unit cube of a substance in unit of time when difference in temperature of two faces is 1°.

Thermal expansion (coefficient of). The fractional change in length (sometimes volume, specified) of a material for a unit change in temperature.

Thermoplastic. (a.) Capable of being repeatedly softened by heat and hardened by cooling. (n.) A material that will soften repeatedly when heated and harden when cooled. Typical of the thermoplastics family are the styrene polymers and copolymers, acrylics, cellulosics, polyethylenes, vinyls, nylons, and the various fluorocarbon materials.

Thermoset. A material that will undergo or has undergone a chemical reaction by the action of heat, catalysts, ultraviolet light, etc., leading to a relatively infusible state. Typical of the plastics in the thermosetting family are the aminos (melamine and urea), most polyesters, alkyds, epoxies, and phenolics.

Thixotropic. Said of materials that are gel-like at rest but fluid when agitated. Liquids containing suspended solids are apt to be thixotropic.

Thread count. The number of yarns (threads) per inch in either the lengthwise (warp) or crosswise (fill) direction of woven fabrics.

Twisting. An operation by which a strand or sliver is given a pre-established number of turns per inch and is thus converted into a yarn, thread, or cord.

Undercut. As a protuberance or indentation that impedes withdrawal from a two-piece, rigid mold.

Vacuum forming. Method of sheet forming in which the plastic sheet is clamped in a stationary frame, heated, and drawn down by a vacuum into a mold. In a loose sense, it is sometimes used to refer to all sheet-forming techniques, including drape forming which involves the use of vacuum and stationary molds.

Viscosity. Internal friction or resistance to flow of a liquid. The constant ratio of shearing stress to rate of shear.

Warp textile. Yarns extending lengthwise in the loom and crossed by the filling yarns.

Wet winding. A term used to describe the process of winding glass on a mandrel where the strand or strands are impregnated with resin, just before contact with the mandrel.

Yarn. A generic term for an assemblage of twisted fibers or strands, either natural or manufactured, to form a continuous yarn suitable for use in weaving or otherwise interweaving into textile materials.

Yarn designation. A term used to indicate the number of original singles (strands) twisted and the number of these units plied to form a yarn or cord. The first letter indicates glass composition by type "E" for electrical; "C" for chemical, etc.; the second letter, the character of the fiber (either the continuous filament or staple fiber); the third letter indicates diameter range of the individual fiber. For example, E plus C plus D (ECD) indicates glass of type E produced as continuous filament (C) of 0.00023-inch average fiber diameter (D). Count or number (following the three letters) represents approximately $\frac{1}{100}$ of the yardage of bare glass fiber per pound; the plies in continuous-filament yarns are designated by two digits following the count number. The first digit shows number of original strands twisted; the second, the number of these units plied. The total number of strands is the product of both numbers (except zero is multiplied as one). Plies in staple fiber yarns are designated by a number following the number that indicates yards per pound.

Index

A-stage cure, 96, 337
Ablation, 10, 29, 32, 61, 157
Abrasion, 53, 60, 71, 101, 318
Acceleration, 238
Acoustical insulation, 61
Acoustic transmission, 287
Adhesives, 15, 74, 82, 100, 140, 215, 286, 337
Advanced Structures, 17
Advantages, 5, 9, 14, 24, 29, 30, 34, 37, 91, 104, 141, 167, 311
Aerojet-General Corp., 60, 116, 123, 131, 172, 174, 204, 212, 231, 250, 251
Aerorove Strand Test, 318
Aerospace Industries Assoc., 47
Aerospace parts, 2, 5, 6, 10, 19, 26, 33, 290
African glass production, 63
Aft closure (*see* End closure)
Air, 106
Aircraft, 3, 15, 32, 42, 70, 98, 154
Air Force, 250
Alkyds, 334, 337
Allyl complex finish, 54, 337
Aluminum, 9, 32, 37, 60, 64, 68, 69, 117, 173, 200, 236
American Optical Co., 56
American Society for Testing and Materials, 76, 91, 95, 109, 250, 280, 282
Analog profile, 199
Anisotropic, 197
Antenna, 3, 17, 27, 152
Antenna tubes, 36
Antioxidants, 75
Appliances, 63 (*see also* Applications)
Applications, 2, 3, 8, 14, 19, 91, 109
Army, 250
Artillery shell, 41
Asbestos, 12, 21, 24, 46, 68, 84, 85, 110, 141, 149, 151, 332, 338
Atlas missile, 6, 27, 32, 89
Attachment, 7, 13, 22, 32, 36, 152, 166, 168, 213, 231 (*see also* Joints)
Autoclave, 24, 103, 133, 338
Automation, 11, 13, 17, 113, 114, 118
Automobiles, 3, 63
Axial load, 28, 89, 236, 256

B.J.Y. finish, 54
B-stage cure, 96, 280, 338
Back-lash, 108
Back tension, 108
Barrel, 37, 82, 84
Battery, 6, 37
Bearing strength, 13, 295, 304
Beryllium, 13, 47, 48, 55, 65, 68
Beta-ray, 287, 290
Binders, 53, 338 (*see also* Finishes)
Black, Sivalls and Bryson, Inc., 4, 22, 50, 134, 147, 149, 230, 291
Boats, 2, 3, 19, 37, 63
Boeing Airplane Co., 189, 280
Bolts, 165
Books—references, 110
Boron fiber, 64
  wire coated, 65

Borosilicates, 47
Boxes, 117
Braiding, 125
Brakes, 8, 108
Break-out mandrel, 127, 131
Brittleness, 72, 90, 151, 282, 289
Brunswick Corp., 125, 202
Buckling, 66, 232, 239, 246, 256, 269, 306
Buildings, 63
Buoys, 3
Burn-out mass ratio, 30
Bushing, 4, 32, 49, 53, 339 (*see also* Orifices)

C-stage cure, 96, 339
Cable, clave, 133
Camelback, 7, 8, 117, 135
Canadian glass imports, 54, 63
Capstans, 126
Cartop boats, 3, 36
Catalyst, 24, 146, 281, 339
Catenary, 319, 339
Centrifugal spinning, 104
Ceramics, 12, 48, 60, 100, 147, 244
Cermets, 100
Chemical properties, 5, 50, 69, 88, 95, 106, 155
Chemical resistance, 47, 51, 70, 91
Chemical storage, 2, 14, 20 (*see also* Tanks)
Chrome complex finish, 54
Circumferentially segmented case, 229
Circumferential pattern, 189
Circumferential wrap, 1, 40, 115, 119, 171
Classification of structures, 173
Cloth, 7, 84
Clothing, 63
Coefficient of expansion, 32, 41, 42, 62, 131, 146, 149, 162, 282, 339
Coefficient of friction, 102
Collapse test of cylinders, 269, 277
Collapsible mandrel, 125, 127, 130, 132
Columbia Products/Shakespeare Co., 12
Combustion, 40
Commercial items, 3, 4, 9, 19, 23, 47, 54, 66, 90, 93
Complex shape, 131
Composite, 6, 30, 58, 70, 90, 132, 179, 204, 243, 321, 339
Compound curvature, 104
Compression, 11, 48, 66, 236, 245, 255, 256, 299, 339 (*see also* Testing)
Cone, 8, 85, 166, 168
Consumable motor case, 29, 30
Consumption, 15
Containers, 14, 27, 58
Controls, 17, 92
Convolute winding, 82, 84, 122
Copper, 68
Corona, 287
Corrosion, 16, 22, 35, 84, 89
Cost, 10, 11, 12, 13, 14, 15, 20, 21, 22, 24, 28, 29, 30, 32, 37, 40, 41, 44, 48, 49, 63, 71, 82, 88, 97, 98, 104, 107, 117, 127, 132, 196, 233, 240, 292, 316
Cotton, 5, 7, 15
Coupling agents, 53 (*see also* Finishes and Sizing)
Cracks, 4, 39, 107, 131, 151, 319
Crazing, 107, 149, 158, 234, 244, 340
Creel, 38, 96, 125, 136, 139, 143, 340
Creep, 41, 151, 310
Cryogenic properties, 155, 156, 244, 340
Cryogenic vessels, 2
Curing, 13, 24, 32, 73, 81, 93, 117, 129, 132, 141, 146, 163, 233, 281, 340
Curing agent, 90, 281
Cyclic fatigue, 155, 166, 242, 243, 260, 277
Cylinders, 60, 117, 160, 164, 166, 168, 180, 193, 269, 301

Dacron, 5
Damascus barrels, 37
Dampening, 43
Data, 5, 15, 20, 36, 48, 56, 58, 59, 62, 65, 67, 68, 77, 81, 92, 95, 99, 110, 135, 155, 156, 160, 162, 166, 168, 173, 180, 184, 196, 205, 214, 234, 236, 237, 240, 243, 259, 277, 279, 282, 314, 319, 322, 324
Data processing, 114, 117, 147
Deep submersive (*see* Hydrospace)
Deep submersive curing, 133
Defects, 12, 30, 136, 149, 178, 289, 316, 323 (*see also* Disadvantages, Failures, Limitations, and Problems)

Definitions, 337
Delamination, 146 (*see also* Defects)
Density, 35, 46, 48, 58, 64, 68, 80, 148, 181, 204, 236, 341 (*see also* Specific gravity)
Department of Commerce report, 43
Dermatitis, 106
Design, 6, 9, 14, 35, 40, 129
  ideal structure, 168, 216
  large case, 229
  principles, 2, 17, 190
  simplified envelope efficiency, 185
  stress, 13, 58, 59
  variables, 117, 145
  winding pattern, 189
Design criteria, 22, 57, 83, 152, 165, 171, 237, 272
Design data, 249, 269 (*see also* Data)
Destructive testing, 17
Deteriorate, 1, 154, 165
Dielectric property, 14, 62, 94, 98, 99, 152, 282, 287, 341
Dip tank, 103, 126
Disadvantages, 10, 12, 27, 29, 91, 100, 104, 106, 126, 141 (*see also* Defects, Failures, Limitations, and Problems)
Douglas Aircraft Co., 10
Drilling, 13
Dry ice, 40
Dry winding, 39, 52, 69, 106, 129
Ductility, 11, 47, 72, 81, 100
Dynamic load, 41, 188

E-glass (*see* Glass fiber type)
Economics, 11, 22, 105 (*see also* Cost)
Efficient structure, 9, 11, 28, 35, 66, 71, 100, 108, 125, 176, 179, 186, 190, 193, 197, 215, 227, 230, 243, 260
Electrical/Electronic parts, 2, 3, 6, 22, 27, 41, 82, 107
Electrical properties, 5, 14, 16, 43, 50, 65, 88, 95, 98, 146, 152
Elevated temperature, 42, 57, 71, 93, 101, 146, 158
Elongation, 201
Emmissivity, 162, 341
End closure, 7, 140, 147, 152, 182, 190, 196, 201, 223, 224, 228, 259
Energy-absorption, 19, 41
England, 54
Envelope efficiency, 186
Environment, 1, 4, 145, 153, 164, 238, 278, 324
Epoxy-novolac resin, 73, 91, 109
Epoxy resin, 12, 21, 38, 48, 73, 89, 90, 104, 155, 159, 235, 318, 334, 341
Equipment manufacturers, 122, 123, 329
Erosion-resistant, 40, 153
European Common Market, 63, 64
Eutectic material, 128, 129
Exports, 61, 63
External hydrostatic ring test, 257
External pressure, 6, 34, 245, 249, 272, 309
Eyelits, 108, 127, 343

Fabric, 54, 117, 162, 342
Fabricate (*see* Filament winding, Manufacturing, Machine, and Winding)
Failure, 24, 81, 85, 108, 274 (*see also* Defects, Disadvantages, Limitations, and Problems)
Fan, 8
Fastening (*see* Attachment)
Fatigue, 35, 71, 79, 148, 155, 165, 244, 246, 260, 278
Ferro Corp., Goldsworthy Engineering Div., 118, 119, 120
Fiber, 7, 15, 46, 61, 342 (*see also* Glass fiber)
  boron, 64
  composition, 67, 68
  diameter, 48, 50, 66, 67, 69, 176, 245 (*see also* Glass fiber diameter)
  flat, 69, 85, 318
  geometry, 67, 69, 176
  heat resistance (*see* Boron and Glass fiber)
  length, 67
  metal, 66
  optics, 287, 290
  tensile strength, 67
Fiber market, 15, 16, 63
Fiber orientation, 175, 184
Fiber packaging (*see* Packaging)
Fiber spacing, 89
Fiber stress, 185, 221

Fiber stress to composite stress ratio, 178
Fibrous, glass, 61
Filament, 10, 49, 65, 197, 342
  tension, 5, 104, 108
  winders, 113, 329
  winders cost, 44
Filament winding around metal chambers, 202, 203
Filament-wound data (*see* Data)
Fillers, 88, 95, 97, 149, 342
Finishes, 7, 40, 50, 69, 73, 146, 268, 279, 342 (*see also* Coupling agents and Sizing)
Firearms, 36
Fishing rod, 3, 63
Flammability, 150, 282
Flat fiber, 69, 85
Flat fiber tape, 50, 69
Flaws, 4
Flexural strength (*see* Testing)
Fluted sandwich, 132
Foldable containers, 142
Forecast, 43, 47
Foreign markets, 61, 63
Foreign trade, 63
Forgings, 315
Formability, 35
Form fitting cure, 133
French glass production, 63
Fungus growth, 150
Furfural resin, 95

Galvanic action, 70
Geodesic path, 199, 227
Geometric shapes, 7, 114, 171
Glass, bulk, 62, 65
Glasses, 46, 49, 60, 102, 289
Glass fiber, 46, 47, 57, 174, 182
  content, 40, 58, 59, 60, 85, 93, 179, 180, 181, 272, 277
  designations, 51
  diameter, 48, 52, 56
  finishes, 54, 102
  flat, 85
  high modulus, 55
  high temperature, 57
  high tensile strength treatment, 57
  hollow, 66
  large diameter, 48
Glass fiber, leached, 61
  lead silicate, 289, 317
  low dielectric, 62
  lubricant, 101 (*see also* Lubricant)
  manufacturing, 49, 332
  market, 15, 16, 63
  metal coated, 151
  nomenclature, 50, 51
  reinforced (*see* Reinforcement)
  sizing (*see* Sizing)
  stress, 163
  suppliers, 332, 336
  surface speed, 4
  tensile strength, 57
  type E, 47, 48, 55, 56, 58, 64, 92, 99, 204, 235
  type HTS, 48, 57, 59, 92, 171, 204, 255, 343
  type lead 498, 62
  type low dielectric 556, 62
  type-S, 57, 58, 60, 92, 99, 166, 168
  type-X994 (*see* Glass fiber, type-S)
  type-YM31A, 55, 56
  virgin, 4, 52, 55
  volume, 66, 181, 243
  world market, 63
Glass marbles, 4, 49, 52, 63, 344
Glass strand, 50
Glossary, 337
Goldsworthy (*see* Ferro)
Golf club, 3, 12
Government agencies, 6, 16, 55, 56, 83, 92, 153, 245, 250
Graphite fiber, 65, 68
Grommet, 41
Growth, 47
Guns, 3, 36, 37, 82, 84, 138, 139, 188, 215

Hardness, 64, 95, 282
Heat absorption, 5, 37
Heat capacity, 10
Heat cleaning, 54, 101, 343
Heat insulation, 11
Heat resistance, 67, 72
Heat shield, 27
Helical pattern, 109, 122, 190, 193, 218
Helical wrap, 115, 129, 235
Helicopter rotor blades, 2
Helix, 40, 171, 185, 193, 223, 232, 277

High modulus, 55, 57
High Tensile Strength glass fiber (HTS), 57
High temperature, 12, 16, 57, 97, 98, 99, 110
History, 1, 4, 9, 22, 26, 32, 33, 37, 63, 113, 122, 155
Holes, 13, 22, 215, 232
Hollow glass fiber, 66 (*see also* Glass fiber)
Homogeneous metal, 34, 66, 205
Honeycomb core, 11, 343
Hooker Chemical Co., 34
Hooke's law, 151, 172, 270
Hoop strength, 2, 85, 194, 236, 237, 270
Hoop-to-helical or longitudinal ratio, 40, 122, 174, 181, 239
Hoop winding, 30, 40, 116, 166, 168, 234
Hot melt, 105
Houze Glass Co., 56
Hughes Aircraft Co., 256
Hull structure, 34
Humidity, 154, 279, 322, 324
Hydraulic tension ring test, 252
Hydroclave, 133
Hydrospace, 2, 7, 10, 33, 34, 171, 245
Hydrostatic tests, 91, 133, 159, 195, 207, 212, 217, 238, 241, 257, 259, 297, 307, 324

Ignition loss, 319, 344
Impact resistance, 27, 70, 95, 98, 244, 291, 310
Imperfections, 237
Imperial Glass, Inc., 56
Imports, 63
Impregnation, 24, 39, 78, 82, 103 (*see also* Dry system and Wet system)
Index of refraction, 282
Industrial applications, 2
Industry, 83 (*see also* Machines and Manufacturers)
Inflatable mandrel, 127
Inorganic material, 1, 48, 88, 100
Insert, 13
Inspection, 316
Insulation, 11, 21, 29, 61, 84, 123, 152, 166, 168, 231
Insulator, 41
Integral case winding, 141
Interfacial resin-glass bond, 101
Interlaminar shear strength, 13, 91, 92, 93, 101, 236, 254, 294
Internal pressure, 6, 11, 24, 28, 140, 182, 190, 216, 257, 268, 308
Interweave, 13
Introduction to winding, 1
Investment, 14, 19, 63
Iron Curtain glass production, 63
Isotensoid pressure vessel, 192, 200, 237
Isotropic, 11, 34, 35, 174, 292
Italian glass production, 63

Jato motors, 2, 33
Johns-Manville Corp., 48
Joints, 83, 140, 164, 203, 229, 232 (*see also* Attachments)

Kellogg, M. W., Co., 122
Knitted, 7

Lamp post, 3, 22, 41
Lamtex/Koppers Co., 26, 43, 94, 115, 126, 130, 136, 137, 143, 201
Leached glass, 61
Leakage, 141, 149
Licensing, 63
Limitations, 11, 101, 215, 269 (*see also* Defects, Disadvantages, Failure, and Problems)
Linde-A-1100 finish, 54
Liners, 22, 24, 29, 38, 85, 123, 140, 156, 160
Liquid fluorine, 156
Lockheed Aircraft Corp., 166, 168
Longitudinally segmented case, 229 (*see also* Modular segmented case)
Longitudinal wrap, 32, 38, 82, 89, 115, 121, 166, 168, 218
Lost-wax process, 132
Low-melting alloys, 128
Low temperature, 11
Lubricant, 54, 69, 126, 142
Lunar probe, 27

McGarry, F. J., Dr., 70
Machine, box, 117
circular, 24, 113

Machine, cost, 44
design, 25, 50, 108, 115, 147
electronic data programming, 114
manufacturers, 24, 122, 123, 329
planetary, 115
rectangular, 117
sizes, 84, 113, 125, 142, 148, 174, 196 (*see also* Winding-size)
tumbling, 117
types, 24, 25, 82, 84, 92, 113, 114, 115, 116, 121, 134, 136, 175, 226
Machine age, 37
Machinery, textile, 7
Machining, 42, 70, 78, 141, 232
Magnesium, 48, 60, 67, 236
Maintenance, 41
Mandrel, 13, 43, 71, 103, 113, 123, 127, 344
coating, 40
design, 107, 121, 129
Manufacturing, 13, 38, 49, 82, 113, 329
variables, 113, 142, 146, 199, 313, 320
Market, 2, 14, 15, 63
Marshall, D. W., 70
Massachusetts Institute of Technology, 70
Material variability, 14, 70, 100, 110, 128, 145, 149, 249, 312
Matrix, 11, 12, 46, 88, 100, 280 (*see also* Resin and Ceramics)
Melamine resin, 102, 150
Meltable mandrels, 127
Melting point, 64, 67, 68, 88
Mercury spacecraft, 27
Metal, 10, 12, 28, 30, 35, 37, 66, 141, 156, 201, 244
tape, 83
wire, 32, 65, 67
Metal chambers, filament wound, 203
Microcrack, 167
Military, 2, 7, 9
Minuteman missile, 27, 28, 30
Missiles, 27, 71, 98
Modular segmented case, 229, 233
Modulus of elasticity, 12, 35, 55, 57, 62, 64, 65, 67, 68, 77, 99, 151, 236, 240, 259, 345
Moisture, 30, 61, 150, 152, 154, 288
Mold growth, 150
Monocoque structure, 42, 70
Motor case, 32, 83 (*see also* Rocket motor)

Narmco Materials, 161
Narmco Research and Development, 6, 128, 159, 175, 185, 192, 242, 252, 253, 280
Natural fibers, 7, 67
Navy, 30, 116, 250
Netting analysis, 104, 186, 190, 191, 193, 196, 197, 199
Nickel, 68, 209
Nike-Zeus missile, 27
NOL-24 finish, 54, 102
NOL ring test, 59, 79, 92, 238, 250, 296, 325
Nondestructive testing, 17, 30, 145, 287
Nonmagnetic, 14
Nonmetallic, 83, 244
Nonwoven felts, 139, 345
North American Aviation–Rocketdyne, 89, 182, 200, 280
Nose cone, 2; 27, 61
Notch sensitivity, 9, 292
Nozzle, 27, 29, 85, 134, 140, 153, 164, 166, 168, 235
Nuclear radiation, 10, 161
Nylon, 5

Oblated spheroid, 7, 148, 191
Ocean, 33, 36
Oceanographic studies, 33
Oil pipe, 14, 22
Oil well tubes, 3
Olin Mathieson Chemical Corp., 37, 82, 84, 96, 138, 139, 188, 215
Organic material, 1, 46, 88, 98, 100, 155, 244
Orifices, 4, 49, 345 (*see also* Bushing)
Orlon, 5
Orthotropic, 148, 175, 188, 270
Outwater, J. O., Dr., 216, 288
Ovaloid, 186, 190, 199, 200, 289
Owens Corning Fiberglas Corp., 48, 53, 56

P.B.I. (*see* Polybenzimidazole)
Packaging, 51, 52, 53, 107, 109, 138, 312
Paint, 41, 101, 162

Parallel layup, 66, 85, 104, 186, 259, 281, 345
Parts, 2, 63 (*see also* Applications)
Penetration, 11
Permeability, 16
Perry, H. A., 145
Pershing missile, 27, 32
Pflederer, F. R., 261, 269
Phenolic resin, 12, 85, 90, 95, 107, 159, 334, 345
Phenyl silane resin, 107, 109
Phosphate oxides, 100
Photoelasticity, 287, 289
Pipe, 3, 14, 15, 22, 40, 71, 84, 125, 174, 260, 262
  life expectancy, 269
Pittsburgh Plate Glass Co., 48
Plaster mold, 123, 127, 130, 131, 231
Plastic, 14, 40, 88, 141, 346
Plastic consumption, 43, 44
Plastic tape, 83
Platinum, 49, 68
Plying, 49, 346
Poisson's ratio, 239, 247, 269, 270, 272, 293
Polar axis, 187, 196
Polar fittings, 190, 200
Polaris missile, 6, 27, 30, 58, 116, 132, 161
Polar openings, 148, 191, 199
Polyamides, 91
Polybenzimidazole resin, 99
Polyester resin, 12, 24, 54, 85, 89, 93, 241, 334, 346
Polyethylene resin, 73, 78, 151
Polyisocyanurate resin, 100
Polymerization, 132, 163, 346
Polymers, 70, 88, 99, 110, 346
Polymetric metal chelate resin, 100
Polyolefins, 73
Polyurethane resin, 99
Ports, 22 (*see also* Holes and Attachments)
Post-cure, 146, 159, 346 (*see also* Cure)
Power factor, 282
Power source, 27, 34, 37
Preheat, 108, 346
Preimpregnated, 84, 97, 103, 106, 117, 121, 143, 147, 234, 286, 318, 321, 336, 347
Prepreg (*see* Preimpregnated)
Pressure chambers, 133
Pressure curing, 133
Pressure vessel, 6, 32, 122, 154, 167, 172, 173, 183
Prestressing, 42, 52, 97, 100, 164, 241, 314, 322
Problems, 22, 140, 141, 155, 175, 199, 249 (*see also* Defects, Disadvantages, Failures, and Limitations)
Process control, 149, 311, 315
Process variables, 17, 147, 311
Production, 29
  forecast, 14, 15, 16, 43
  history, 14, 43
  mass, 20, 92
Products, 1, 2, 14
Propellant, 40
Properties, 51, 58, 62, 93, 109, 145, 152, 156, 165, 234
Pulley, 108

Quality control, 17, 37, 91, 246, 249, 288, 311, 316
Quartz, 12

Radiation, 161
Radiography, 287, 288
Radome, 2, 27, 43, 94, 98
Railway tanks, 3, 4, 19, 21, 50, 134, 149, 230, 291
Rayon, 16
Rectangular shapes, 4
Red Thread pipe, 261
References, 18, 44, 86, 110, 144, 168, 247, 326
Reflectivity, 161
Refractories, 68
Reinforced plastics, 15, 27, 36, 63, 88, 159, 175
Reinforcements, 11, 46, 76, 88, 174, 182, 246, 332, 336, 347
Release products, 91
Reliability tests, 9, 29, 31, 66, 325
Repair, 35, 145
Research and development, 6, 9, 16, 19, 23, 30, 55, 70, 79, 83, 99, 100
Resin, 12, 15, 72, 88, 163, 237, 270, 280, 319, 334, 336, 347
  application, 103

Resin, binder, 54
bulk strength, 75
content, 58, 59, 90, 92, 104, 109, 135, 147, 239, 243
dispenser, 94
elongation, 90
gel, 90, 343
glass interfacial bond, 101, 280
layer, 89
manufacturers, 334
properties, 95, 98
shrinkage, 132, 281
specification for elevated temperature, 93
tests, 280
thickness, 89
volume, 89
Resinous matrices (*see* Resin)
Reverse curvature, 13
Ribbon, 50, 83, 107, 126, 134, 312, 314, 347
Rifle (*see* Guns)
Ring specimens (*see* NOL ring test)
Ring stiffeners, 36
Rocket motor, 2, 9, 10, 19, 27, 31, 54, 58, 71, 89, 116, 155, 158, 166, 168, 173, 175
Rollers, 108, 127, 136, 142
Room temperature characteristics, 91, 93, 101, 268
Room temperature fiber strength, 57
Rotating mechanisms, 8
Roving, 7, 21, 32, 47, 49, 53, 97, 106, 119, 135, 321, 323, 347
Rubber, 24, 127, 131, 134, 151, 322 (*see also* Liners)
Rust, 37, 39

S-glass (*see* Glass fiber, type-S)
Safety factor, 37
Sales, 1, 63
Salt water, 23, 33
Sandwich construction, 11, 35, 132, 201, 347
Scale down model, 149, 153
Scout missile, 27, 28
Secant modulus of elasticity, 293
Segmented motor case, 29, 31, 123, 131, 152, 229
Self-extinguishing, 150
Sh ar strength, 13, 151, 178, 304, 325
Shock absorption, 11, 27, 43
Shotgun (*see* Gun)
Shrinkage, 42, 142, 281, 282, 345
Silane finish, 54
Silica glass, 48, 60, 102
Silicone resin, 12, 98, 107, 159
Silver, 68
Simplified envelope efficiency, 185
Sizing, 4, 53, 74, 101, 150, 154 (*see also* Finish and Coupling agents)
Skirts, 31, 164, 166, 168
A. O. Smith Corp., 254, 255, 262, 263, 264, 266, 267, 269, 271, 273, 274, 275, 276
Society of Plastics Engineers, 280
Society of Plastics Industry, 109
Soft metal, 41
Solar radiation, 161
Solid propellant, 10, 28, 31, 116, 141, 174, 348
Solid resin, 105 (*see also* Resin)
Solvent, 104, 348
Sonic energy, 11
South American glass production, 63
Space, 10, 26, 29, 142
Spacecraft, 27
Sparrow missile, 206, 210, 211
Spaulding Fibre Co., 42
Specifications, 58, 69, 92, 145, 153, 167, 249, 260, 294, 318
Specific gravity, 67, 150, 282, 348 (*see also* Density)
Specific heat, 62, 162
Specific impulse, 30
Specific strength, 7, 65, 80, 236
Sphere, 7, 26, 33, 117, 148, 154, 166, 171, 183, 191, 279
Spinning, 7
Split-ring tension test, 251
Spool, 50, 107, 117, 119, 138, 312
Springs, 19
Squeeze rolls, 127
Standardization, 17, 92, 109, 147, 168, 249
Staple fibers, 67
Starch, 4
Statistics, 14, 22, 44, 61, 63
Steel, 9, 20, 22, 28, 30, 38, 47, 127, 166, 168, 173, 202, 240, 312

Steel tape, 83, 134, 229
Steel wire, 28, 38, 41, 65, 68, 151, 236, 239, 240
tensile strength, 47, 60, 68, 70, 77, 83
Stiffener, 11, 35
Storage tanks, 14, 20, 32, 155
Strand, 49, 52, 116, 348
Strength-weight ratio, 5, 14, 16, 26, 40, 41, 43, 46, 61, 66, 68, 71, 156, 171, 190, 195, 235, 260, 292
Stress, analysis, 55, 141, 180
attachments, 215
concentrations, 164, 242
data, 58, 59, 238
fundamental, 180
residual, 128
pattern, 40, 196
variables, 148, 163
Stress-strain relationships, 207, 239, 241, 270, 310
Structural performance growth, 47
Submarine, 2, 24
Subscale (*see* Scale down)
Surface speed-glass forming, 4
Surface treatment, 101, 150
Sweden, 8, 23, 24
Switch gear, 41
Synthetic material, 7, 16, 67, 88, 98, 349

Tacky resin, 106, 108, 149, 286, 349
Tanks, 2, 10, 19, 20, 28, 142, 149, 155, 173, 291
Tapes, 1, 7, 8, 23, 24, 32, 39, 41, 50, 63, 82, 83, 115, 135, 139, 141, 147, 153, 161, 215
Teflon, 73, 127
Temperature characteristic, 42, 99, 244 (*see also* Elevated, Low, and Room temperatures)
Tensile strength, 58, 59, 67, 68, 80, 85, 92, 99, 135, 222, 236, 243, 318 (*see also* Testing)
filaments, 5, 52, 56, 65
Tension control, 7, 50, 108, 113, 117, 135, 137, 143, 147, 250, 314 (*see also* Winding tension)
Terms, 51, 69, 88, 98 (*see also* Glossary)
Terrior missile, 27
Testing, 17, 23, 34, 44, 145, 153, 159, 238
Test procedures, 238, 249, 370
Tests, basic, 292
experimental, 291
Test specimen, flat, 76, 280, 294
Texaco Experimental Inc., 64
Textile, 5, 7, 17, 47, 49, 63, 71, 125, 349
Textile bobbins, 3
Thermal characteristics, 39, 64, 70, 88, 100, 160, 173, 236, 244, 349
Thermal expansion, 40, 42, 95 (*see also* Coefficient of expansion)
Thermal insulation, 10, 140
Thermal shock, 27, 100, 159
Thermoplastic resins, 349
Thermosetting resins, 91, 95, 141, 349
Thickness-to-diameter ratio, 149
Thin-metal liner, 38
Thin-shell theory, 34, 148
Thin wall, 11, 33, 58, 148, 159, 183, 239, 269
Thixotropic, 349
Thompson Ramo Wooldridge, Inc., 85, 114, 121, 153
Thor missile, 132
Thrust loads, 28, 29, 89, 157
Titanium, 28, 30, 47, 65, 68, 203, 236, 240
Titan missile, 28, 153
Tooling, 28, 44, 120, 196, 240, 252 (*see also* Mandrel and Machine)
Toroidal, 148, 192
Torpedo hulls, 2, 33, 34
Torsion, 51
Torsion bars, 19
Toughness, 9, 35, 100, 151, 319
Transparency characteristic, 40, 70
Treatments, 7
Tree surgery booms, 41
Triallylcyanurate resin, 94
Truck booms, 41
Truck springs, 19
Tubing (*see* Pipe)
Tungsten wire, 67, 68
Twist, 49, 51, 52, 109, 136, 349

Ultrasonic, 287
Undercarriages, 43
Underwater buoys, 2
Unidirectional, 7, 11, 41, 84, 173, 188, 245

United Kingdom, 63
United States, 7, 16, 22, 43, 54, 63, 64, 90
United Technology Corp., 157, 158
Uses (*see* Applications and Parts)

Vacuum, 103, 234, 281, 349
Vapor deposition, 64
Vermont Ball Winding System, 226
Vessels, 34, 60, 154
Vibration, 11
Viscosity, 49, 76, 78, 90, 93, 104, 126, 320, 349
Voids, 92, 106, 148, 150, 161, 243
Volan A finish, 54, 102
Volatiles, 91
Volume content, 58, 59, 181
Volume resistivity, 62, 282
Volumetric expansion, 200

Wall thickness, 149 (*see also* Thin wall)
Walter Kidde & Co., 122
Warp, 7, 349
Washout sand mold, 233
Waste material, 106
Water absorption, 91
Water-tight, 14, 98, 133
Water vapor, 4
Wax, 132
Weathering, 16, 153
Weave, 7
Weight-strength ratio (*see* Strength-weight ratio)
Welding, 22, 35, 315, 316
West German glass production, 63
Wet winding, 91, 103, 107, 129, 138, 350
Winchester Model 59, p. 37
Winder, 13
Winding, diameters, 28
Winding equipment, 96, 106, 174, 175, 329
Winding machine, 44, 108, 121, 138, 139, 165 (*see also* Machines)
Winding mandrel, 107
Winding method, 29, 119
Winding pattern, 2, 9, 84, 85, 118, 125, 140, 147, 154, 185, 189, 193, 199, 221
Winding process, 91, 103
Winding size, 29, 35 (*see also* Machine size)
Winding tension, 104 (*see also* Tension controls)
Winding tube for glass, 49
Winding tubes, 52
Winding variables, 51, 148
Wire, 63 (*see also* Steel wire)
Wire cleaning, 69, 73, 76
Wire coating, 69
Wire data, 64, 67, 68, 77, 83
Wire diameter, 67, 69, 70, 72
Wire drawing, 69, 72
Wire epoxy, 70
Wire shapes, 67, 69
Wire wound, 66, 70, 78
Wire wrap, 1, 66
Wool, 5, 7, 15
World fibrous-glass market, 63
Woven fabrics, 7, 63, 139, 238
Woven tapes, 32, 47, 84
Wrapping pattern (*see* Winding pattern)

X-ray, 129, 287, 289

Yarn, 7, 47, 49, 53, 63, 350

Zinc, 70